OUR PECULIAR MOTION AWAY FROM THE LOCAL VOID

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ABSTRACT

The peculiar velocity of the Local Group of galaxies manifested in the cosmic microwave background dipole is found to decompose into three dominant components. The three components are clearly separated because they arise on distinct spatial scales and are fortuitously almost orthogonal in their influences. The nearest, which is distinguished by a velocity discontinuity at \( \sim 7 \) Mpc, arises from the evacuation of the Local Void. We lie in the Local Sheet that bounds the void. Random motions within the Local Sheet are small, and we advocate a reference frame with respect to the Local Sheet in preference to the Local Group. Our Galaxy participates in the bulk motion of the Local Sheet away from the Local Void. The component of our motion on an intermediate scale is attributed to the Virgo Cluster and its surroundings, 17 Mpc away. The third and largest component is an attraction on scales larger than 3000 km s\(^{-1}\) and centered near the direction of the Centaurus Cluster. The amplitudes of the three components are 259, 185, and 455 km s\(^{-1}\), respectively, adding collectively to 631 km s\(^{-1}\) in the reference frame of the Local Sheet. Taking the nearby influences into account, particularly that of the Local Void, causes the residual attributed to large scales to align with observed concentrations of distant galaxies and reduces somewhat the amplitude of motion attributed to their pull. Concerning the motion of \( \sim 260 \) km s\(^{-1}\) away from the Local Void, given the velocities expected from gravitational instability theory in the standard cosmological paradigm, the distance to the center of the Local Void must be at least 23 Mpc from our position. The Local Void is extremely large.

Subject headings: dark matter — galaxies: distances and redshifts — large-scale structure of universe

Online material: color figures, machine-readable tables, mpeg animations

1. INTRODUCTION

The dipole anisotropy seen in the cosmic microwave background (CMB) temperature map (Fixsen et al. 1996) is compelling evidence that the solar system has a large peculiar motion with respect to the overall cosmic expansion. There are known local components to this motion, including the orbital velocity of the Sun in the Milky Way, and the attraction of our Galaxy toward M31. Once these components are taken into account, it is found that the Local Group of galaxies has a peculiar motion of over 600 km s\(^{-1}\) in a well-established direction.

Soon after the discovery of the CMB dipole, the coincidence in direction of our motion with prominent large-scale structure was noted (Shaya 1984); then evidence was found for flows of nearby galaxies toward this direction (Lynden-Bell et al. 1988). There has been great interest in trying to identify the dominant source, or at least the characteristic distance, of the “great attractor” causing our large-scale motion. This interest is well summarized in several conference proceedings (Rubin & Coyne 1988; Bouchet & Lachieze-Rey 1993; Courteau & Willick 2000). The issue has been complicated by the observation that two important structures lie in the general direction of our motion: the Norma-Hydra-Centaurus complex in the foreground and the enormous Shapley concentration in the background (Scaramella et al. 1989; Raychaudhury 1989). The debate continues regarding the relative importance of these structures on our motion (Kocevski & Ebeling 2006; Erdoğan et al. 2006a).

There has been a long-standing appreciation that there are significant dynamical influences on intermediate scales within what has traditionally been called the Local Supercluster. Our galaxy is known to experience a pull toward the Virgo Cluster at the heart of the Local Supercluster (Tonry & Davis 1981; Aaronson et al. 1982; Hoffman & Salpeter 1982; Tully & Shaya 1984; Tonry et al. 2000). However, the story on intermediate scales is more complicated than just an attraction centered on or near the Virgo Cluster. The numerical action method (NAM) models of Shaya et al. (1995) assign mass according to the complex distribution of light and provide a reasonable description of galaxy motions. Still, NAM reconstructions have not yet provided a fully satisfactory explanation of the “local velocity anomaly” (Tully 1988a; Faber & Burstein 1988; Tully et al. 1992). We use the term to describe the pattern of negative motions with respect to Hubble expansion of galaxies in a neighboring filament called the Leo Spur in the Nearby Galaxies Atlas (Tully & Fisher 1987).
In the present paper we return to the problem of the local velocity anomaly. Imaging with Hubble Space Telescope (HST) has provided a wealth of accurate distances to nearby galaxies based on measures of the luminosity of stars at the tip of the red giant branch, the TRGB method (Karachentsev et al. 2004, 2006). In addition, over the years many other good distances have become available. Particularly important for this work include those provided by the HST Cepheid Key Project (Freedman et al. 2001), the Surface Brightness Fluctuation (SBF) study of Tonry et al. (2001), and two catalogs of luminosity–line width distances, one a sample of extreme edge-on galaxies with 2MASS magnitudes that has been discussed by Karachentsev et al. (2002a), and the other an extension of the sample discussed by Tully & Pierce (2000). These new observations of distances have clarified that the phenomenon referred to as the “local velocity anomaly” definitely exists, but it is so much more extensive than previously suspected that the adjective “local” may not be appropriate. It will be shown that the observed anomalous motion has nothing to do with the known pull toward the Virgo Cluster nor to the large-scale great attractor(s).

2. A CATALOG OF GALAXY DISTANCES

Our database is an outgrowth of the Nearby Galaxies Catalog (Tully 1988b), and for the current discussion has the same limit of 3000 km s$^{-1}$. At present we have distance estimates for 1791 galaxies in 743 groups in this volume derived from four different methods. The reference scale for our distances is set by the HST Cepheid Key Project observations (Freedman et al. 2001). Including all sources, we have 51 distances by the Cepheid method. Next we add galaxies with TRGB distance estimates. Individual TRGB distances are of comparable quality to the Cepheid values and are demonstrated to be on a consistent scale (Dolphin et al. 2003; Sakai et al. 2004; Rizzi et al. 2007). Procedures for measuring the TRGB are discussed by Sakai et al. (1996) and Makarov et al. (2006). Distance moduli are directly compared in Figure 1a for 14 galaxies with both Cepheid and TRGB measurements. There are 221 TRGB estimates in the present sample. Third, we accept the SBF measures of Tonry et al. (2001) and Mei et al. (2007). The Tonry measures are available for 299 galaxies around the sky, while the Mei sample of 84 galaxies is restricted to the Virgo Cluster and a projected group. The claimed accuracies with SBF are comparable with the Cepheid and TRGB accuracies. The zero point for SBF distances is confirmed to agree with the zero point for SBF distances is confirmed to agree with the HST Cepheid Key Project results.

This zero point is set by 40 galaxies with Cepheid or TRGB distance measures. Here is our current calibration:

\[
M_B^{h,i,k} = -19.99 - 7.27(W_R - 2.5),
\]

\[
M_R^{h,i,k} = -21.00 - 7.65(W_R - 2.5),
\]

\[
M_I^{h,i,k} = -21.43 - 8.11(W_R - 2.5),
\]

\[
M_H^{h,i,k} = -22.17 - 9.55(W_R - 2.5),
\]

where the superscripts on the B, R, I, and H absolute magnitudes indicate corrections have been made for obscuration within our Galaxy (b) and due to the inclination of the target galaxy (i) and for redshift effects (k) (Tully & Pierce 2000). The parameter $W_R$ is a measure of the inclination-corrected neutral hydrogen line width (Tully & Fouqué 1985). The optical band magnitudes $B$, $R$, and $I$ are “total” values. The near-infrared $H$ magnitudes are aperture values in the system of Aaronson et al. (1986).

The other luminosity–line width sample is composed of edge-on galaxies with 2MASS K-band photometry (Karachentsev et al. 2002a) restricted to less than 3000 km s$^{-1}$. This sample contributes 402 distances, 178 already included. The substantial overlap between the two luminosity–line width samples provides confirmation that the zero points are the same and gives rms agreement per measure of 0.39 mag. The excellent agreement in distance moduli between the luminosity–line width and other measures is shown in Figure 1b. Figure 1c compares all cases in the current sample with distance measurements by more than one method.

The luminosity–line width distance estimates are considered to have an accuracy of 20% rms for a single observation. They are less accurate than those obtained with the procedures previously discussed, but are much more numerous. SBF observations are restricted to early-type galaxies that tend to reside together in high-density environments. Luminosity–line width observations are restricted to spiral galaxies that are more widely distributed. The combination of the two provides a rich sampling of the distribution of galaxies and their motions throughout the Local Supercluster.

Our current database of distances for galaxies within 3000 km s$^{-1}$ is provided in two tables that can be accessed in their entirety in the online Journal. Table 1 identifies the 1791 individual galaxies with measured distances. The column information is as follows. Columns (1), (2): 12000 equatorial coordinates. Column (3): Principal Galaxies Catalogue (PGC) name from the Lyon Extra-galactic Database. Column (4): Common name. Column (5): Group ID for cross-reference with Table 2. Column (6): NBG ID, the group ID in the Nearby Galaxies Catalog (Tully 1988b). Columns (7), (8): Galactic longitude and latitude. Columns (9), (10): Supergalactic longitude and latitude. Column (11): Numeric morphological type code. Column (12): Differential Galactic reddening $E(B-V)$ (Schlegel et al. 1998). Column (13): Total blue magnitudes, mostly from the Third Reference Catalogue (de Vaucouleurs et al. 1991). Columns (14)–(17): Velocities in the reference frames of the Sun, the Galactic center, the Local Sheet (defined later), and the CMB, in km s$^{-1}$. Columns (18)–(30) are filled if the galaxy has a luminosity–line width distance estimate based on the revised Tully & Pierce (2000) calibration. Column (18): Photometrically derived ratio of minor to major axes $b/a$, related to the galaxy inclination $i$ by $\cos i = \left((b/a)^2 - q_0^2)/1 - q_0^2\right)^{1/2}$, where $q_0 = 0.2$ is taken as the axial ratio of a spiral galaxy seen edge on. Column (19): Number of sources for

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1 See http://leda.univ-lyon1.fr/.
the measurement of axial ratio. Column (20): Total $B$ magnitude from CCD area photometry. Columns (21), (22): Total $R$ magnitude and number of sources for $R$ magnitude. Columns (23), (24): Total $I$ magnitude and number of sources for $I$ magnitude. Columns (25), (26): $H_{0.5}$ aperture magnitude and number of sources of $H$ photometry. Columns (27), (28): Heliocentric velocity and line width based on $H\alpha$ observations; the line width is the parameter $W_\lambda/2$ defined by Tully & Fouqué (1985), including rectification from the viewing inclination to edge-on, defined to agree statistically with twice the maximum rotation velocity. Columns (29), (30): Distance modulus and uncertainty determined from the luminosity–line width method, where the uncertainty reflects a weighting of the separate bandpasses. Column (31): Distance modulus determined in the case of a galaxy from the flat galaxy–2MASS sample; an uncertainty of 0.40 mag is accepted in these cases. Columns (32), (33): Distance modulus given by either the surface brightness fluctuation method ($s$), the brightest red giant branch stars ($r$), or the Cepheid period–luminosity relation ($c$), and indication of the source, $s$, $r$, or $c$; an uncertainty of 0.2 mag is accepted in these cases.

In Table 2 information is reassembled and averaged within 743 groups (including groups of one). The columns are: Column (1):
### TABLE 1
**Distance Estimates for 1791 Galaxies**

| R.A. (J2000) | Decl. (J2000) | PGC | Name | Group ID | NBG ID | ϵ | b | SGL | SGB | T | E(B−V) | BT | V_c | V_GSR | V_LS | V_CMB |
|--------------|--------------|-----|------|----------|--------|---|---|-----|-----|----|--------|----|-----|-------|------|-------|
| 00 01 58.5   | −15 27 41    | 143 | WLM |          |        |   |   |     |     |    |        |    |     |       |      |       |
| 00 03 15.0   | +16 08 43    | 218 | NGC 7814 | 1211 | 65   | −6 | 6  | 106.4094 | 45.1749 | 309.0612 | 16.4021 | 2 | 0.045 | 11.57 | 1054 | 1194  |
| 00 03 58.7   | +20 45 06    | 279 | NGC 7817 | 1178 | 64   | −8 | 8  | 108.2271 | 40.7610 | 313.8132 | 17.1426 | 4 | 0.058 | 12.74 | 2308 | 2457 |
| 00 06 20.1   | −41 29 45    | 474 | ESO 293-034 | 1088 | 61   | 0  | 16 | 332.8271 | −72.9123 | 253.5419 | −1.5693 | 6 | 0.017 | 13.64 | 1516 | 1482 |
| 00 08 13.9   | −34 34 45    | 621 | ESO 349-031 | 233  | 14   | 13 | 13 | 351.4707 | −78.1179 | 260.1831 | 0.4018 | 10 | 0.012 | 15.81 | 229  | 217  |
| 00 08 20.7   | −29 54 58    | 627 | NGC 0007 | 1096 | 61   | −18| 18 | 13.9903 | −80.1369 | 264.5891 | 1.9321 | 5 | 0.014 | 14.35 | 1496 | 1499 |
| 00 09 56.4   | −24 57 48    | 701 | NGC 0024 | 355  | 19   | −8 | 7  | 43.6887 | −80.4344 | 269.3877 | 3.2260 | 5 | 0.019 | 12.10 | 553  | 572  |
| 00 11 24.7   | −41 23 53    | 800 | ESO 293-045 | 1088 | 61   | 0  | 16 | 330.3100 | −73.5343 | 253.9490 | −2.4348 | 8 | 0.011 | 15.25 | 1466 | 1430 |
| 00 15 08.4   | −39 13 13    | 1014 | NGC 0055 | 234  | 14   | 13| 13 | 332.6677 | −75.7388 | 256.2418 | −2.4123 | 9 | 0.013 | 8.47  | 125  | 95   |
| 00 15 31.5   | −32 10 51    | 1038 | ESO 410-005 | 234  | 14   | 13| 13 | 357.8407 | −80.7103 | 262.9460 | −0.2577 | −5 | 0.014 | 15.17 | 0    | 0    |
| 00 17 45.5   | +11 27 01    | 1160 | NGC 0063 | 1213 | 65   | 6  | 6  | 109.8744 | −50.5655 | 305.1594 | 11.9146 | 5 | 0.111 | 12.73 | 1160 | 1282 |
| 00 20 23.1   | +59 17 35    | 1305 | IC 0010 | 222  | 14   | −12| 12 | 118.9699 | −3.3395 | 354.4176 | 17.8657 | 10 | 1.560 | 11.78 | −346 | −161 |

### Note
Table 1 is published in its entirety in the electronic edition of the Astrophysical Journal. A portion is shown here for guidance regarding its form and content.
A unique group identification number; appears in column 4 of Table 1 for individual galaxies. Column (2): NBG ID, as in column (5) of Table 1. Columns (3), (4): Galactic longitude and latitude of group. Columns (5), (6): Supergalactic longitude and latitude of group. Column (7): Logarithm of absolute luminosity summed over all estimates for group members. Columns (8)–(11): Group averaged velocities in reference frames of the Sun, the Galactic center, the Local Sheet, and the CMB, in km s\(^{-1}\). Columns (12), (13): Distance modulus and uncertainty, averaged over all estimates for group members. Columns (14)–(17): Distance, and components of distance in the supergalactic SGX, SGY, and SGZ directions, in Mpc. Column (18): Peculiar velocity if \(H_0 = 74\) km s\(^{-1}\) Mpc\(^{-1}\), \(V_{pec} = V_{LS} - H_0 d\), in km s\(^{-1}\), where \(V_{LS}\) is the velocity in column (10), and \(d\) is the distance in column (14). Columns (19)–(21): Number of galaxies in group with luminosity–line width distance measures from the extended Tully-Pierce sample, the averaged distance modulus from luminosity–line width measures, and the assigned uncertainty. Columns (22)–(24): Number of galaxies in group with distances measures from the flat galaxies–2Masse sample, the averaged modulus, and uncertainty. Columns (25)–(27): The sum of the number of galaxies in the group with surface brightness fluctuation, tip of the red giant branch, or Cepheid distance measures, the averaged modulus, and uncertainty.

3. THE PECULIAR VELOCITY FIELD WITHIN 3000 km s\(^{-1}\)

Knowledge of distances, \(d\), permits a subtraction of cosmic expansion velocities, \(H_0 d\), from observed velocities, \(V_{obs}\), to give \(V_{pec}\), the radial component of what are referred to as peculiar velocities:

\[
V_{pec} = V_{obs} - H_0 d, \tag{5}
\]

where \(H_0\) is the Hubble constant.

The decomposition of observed velocities into cosmic expansion and peculiar velocity terms requires knowledge of the Hubble constant, which is defined as

\[
H_0 = \langle V_{obs}/d \rangle, \tag{6}
\]

that is, a measure of the expansion rate over a sufficiently large domain of the universe that peculiar motions cancel and have a negligible impact.

Imagine that observers make a zero-point error in the determination of distances; i.e., on average, distances are off by a factor \(f_e\) from true values, \(d_{true} = f_e d_{measured}\). Then the product \(H_0 d\) has terms \(f_e\) in the numerator and denominator that cancel. The consequence is the well-known result that peculiar velocity measures are insensitive to a zero-point error in the distance scale as long as the assumed value of \(H_0\) is consistent with the scale of measured distances.

Yet there is a problem. We are not guaranteed that peculiar motions are negligible in the volume we sample to establish \(H_0\). For example, we live in the Local Supercluster, which is an overdense part of the universe. It would not be surprising if there were a net infall within this region. As a general statement, most observers in the universe must live in overdense places, with a local retardation of the cosmic expansion, and will tend to measure a value of \(H_0\) locally that is smaller than the cosmic value. Or, as another example, an observer might live on the outskirts of a large concentration, and the preponderance of nearby galaxies in the direction of the concentration might be rushing away, toward the concentration. The large number of these receding objects might cause \(H_0\) to be overestimated.

In the present case, it is rather clear that the volume of our sample, limited to 3000 km s\(^{-1}\), is too small to define \(H_0\) without bias. It might be tempting to assert that \(H_0\) is known, for example from CMB measurements (Spergel et al. 2003). However such a value

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**TABLE 2**

AVERAGED DISTANCE ESTIMATES FOR 743 GROUPS

| Group ID | NBG ID | \(\ell\) | \(b\) | SGL | SGB | \(\log M_B\) | \(V_{LS}\) | \(V_{GSR}\) | \(V_{CMB}\) | \(\mu\) | \(\epsilon_{\mu}\) | \(d\) |
|----------|-------|-----|-----|-----|-----|----------|--------|--------|--------|---------|--------|-----|
| 1............ | 11−11 | 282.93 | 74.45 | 102.70 | −2.35 | 12.26 | 1091 | 1042 | 999 | 1421 | 31.13 | 0.10 | 16.8 |
| 2............ | 11−21 | 299.61 | 66.04 | 112.68 | −1.26 | 11.11 | 900 | 832 | 776 | 1235 | 30.96 | 0.13 | 15.6 |
| 3............ | 11−31 | 291.06 | 68.94 | 108.83 | −3.18 | 9.77 | 2011 | 1946 | 1894 | 2349 | 30.70 | 0.36 | 13.8 |
| 4............ | 11−41 | 289.24 | 65.45 | 111.57 | −5.36 | 11.12 | 1615 | 1538 | 1480 | 1960 | 31.23 | 0.11 | 17.6 |
| 5............ | 11−51 | 283.70 | 69.13 | 107.33 | −5.36 | 11.25 | 1079 | 1011 | 960 | 1421 | 31.85 | 0.11 | 23.4 |
| 6............ | 11−61 | 245.25 | 76.24 | 94.22 | −6.75 | 9.53 | 1147 | 1106 | 1073 | 1472 | 29.64 | 0.36 | 8.5 |
| 7............ | 11−71 | 299.14 | 62.46 | 116.08 | −2.64 | 10.38 | 1565 | 1486 | 1424 | 1904 | 30.98 | 0.37 | 15.7 |
| 8............ | 11−81 | 304.29 | 62.04 | 117.17 | −0.48 | 10.23 | 1233 | 1158 | 1096 | 1566 | 31.81 | 0.15 | 23.0 |
| 9............ | 11−91 | 283.19 | 68.68 | 107.56 | −5.78 | 10.09 | 748 | 679 | 626 | 1091 | 32.15 | 0.28 | 26.9 |

**NOTE.**—Table 2 is published in its entirety in the electronic edition of the Astrophysical Journal. A portion is shown here for guidance regarding its form and content.
might not be consistent with the zero-point scale of the distance measures. Here we avoid the issue of which scale might be “correct,” if there should be an inconsistency. We simply note that on the scale of our present sample is not well defined, because it does not extend in a self-consistent manner to large enough distances.

These caveats regarding $H_0$ are mentioned because, as will be seen, there are large deviations from cosmic expansion seen within the 3000 km s$^{-1}$ region whatever reasonable value is assumed for $H_0$. Selecting a larger value of $H_0$ enhances a pattern in comoving coordinates of overall infall while selecting a smaller value of $H_0$ creates a trend toward outflow.

3.1. The Pattern of Peculiar Velocities and a Choice of $H_0$

With specification of $H_0$, peculiar velocities can be found through equation (1) for all galaxies with measured distances. Although there is uncertainty in $H_0$, observations constrain it to lie roughly within $70 < H_0 < 80$ km s$^{-1}$ Mpc$^{-1}$. The HST Key Project best estimate is toward the low end of this range (Freedman et al. 2001), while our own best estimate is toward the high side (Tully & Pierce 2000).

The series of panels in Figure 2 illustrates the effect of varying the choice of $H_0$ from 70, through 75, to 80 km s$^{-1}$ Mpc$^{-1}$. Negative peculiar velocities are coded blue, while positive peculiar velocities are red. Large symbols are given in cases with Cepheid, TRGB, or SBF distances, and small symbols are given in cases with the numerous but individually less accurate luminosity–line width distances. The tiny black dots locate galaxies positioned according to their observed velocities but lacking distance measures. There are 8795 galaxies in the $V < 3500$ km s$^{-1}$ cube, part of a compilation drawn mainly from the Center for Astrophysics Redshift Catalog$^2$ circa 2002.

Patterns of average positive and negative peculiar velocities can be seen in large swaths across these figures. There is a prominent overall pattern of infall in the maps with $H_0 = 80$ km s$^{-1}$ Mpc$^{-1}$, which successively diminishes in the $H_0 = 75$ and $H_0 = 70$ maps. These negative velocities dominate the map in a large sector toward the Virgo Cluster, the most populated region, and almost everywhere at negative SGZ; i.e., below the equatorial plane in the supergalactic coordinate system. By contrast, peculiar velocities tend to be positive in the quadrant south of the Galactic plane (SGY negative) and above the supergalactic equator (SGZ positive). Peculiar velocities also tend to swing positive at greater distances in the general direction of the motion indicated by the CMB dipole (near the supergalactic equator toward SGX negative). The positive velocities are most pronounced in maps with $H_0 = 70$, but the trends persist with $H_0 = 75$ and 80.

The major point we would make with this part of the discussion is that the overall patterns in the peculiar velocity field are similar whatever value for $H_0$ is considered in the range of reasonable values between 70 and 80 km s$^{-1}$ Mpc$^{-1}$. The direction and amplitude of the inferred peculiar velocity of our Galaxy is insensitive to the choice of $H_0$ over this range. In § 3.4, a weak preference will be found for $H_0 = 74$ km s$^{-1}$ Mpc$^{-1}$. The amplitudes of peculiar velocities of individual galaxies other than our own depend on the choice of $H_0$. The fundamental results of this paper are based on the well-determined motion of our Galaxy and the patterns, but not critically the amplitudes, of other galaxies in our sample.

3.2. Galactic and Local Group Standards of Rest

As a preliminary step, we review the status of the solar motion with respect to the galaxies of the Local Group. Here, as in the subsequent discussion, the amplitude and direction of our motion is determined by minimizing a condition of the form

$$\min \left[ \sum_{i=1}^{N} (V^i - H^i \dot{x}_i + \dot{y}_i + \dot{z}_i V^i)^2 \right].$$

The $N$ galaxies to be considered with measured distances $d^i$ and observed velocities $V^i$ have Galactic coordinates $\ell_i$, $b_i$, which decompose along cardinal axes as

$$\dot{x}_i = \cos \ell_i \cos b_i$$
$$\dot{y}_i = \sin \ell_i \cos b_i$$
$$\dot{z}_i = \sin b_i$$

(or the equivalent $\hat{X}$, $\hat{Y}$, $\hat{Z}$ in supergalactic coordinates $L$, $B$). One solves for the expansion component $H$ and the cardinal components of our motion with respect to the chosen rest frame, $V_x$, $V_y$, $V_z$. The term $H$ can alternatively be fixed at a reasonable value or left as a free parameter. In general, the solutions are more stable if $H$ is fixed.

In the first step of the analysis of motions within the Local Group, heliocentric velocities are considered, and reference sample is $N = 40$ galaxies within 1.1 Mpc, hence within roughly the zero-velocity surface or radius of first turnaround to infall in the Local Group (Karachentsev et al. 2002b). For this gravitationally bound sample, the Hubble parameter is set to $H = 0$ km s$^{-1}$ Mpc$^{-1}$. The Sun is found to have a motion of $(V_x^S + V_y^S + V_z^S)^1/2 = 318 \pm 20$ km s$^{-1}$ toward $\ell = 106 \pm 4$, $b = -6 \pm 4$ ($L = 349$, $B = +30$). This solution is in good agreement with previous results (Yahil et al. 1977; Karachentsev & Makarov 1996; Courteau & van den Bergh 1999). The close agreement with earlier work is expected, since the Local Group reference information has only been augmented incrementally. It is instructive to note that the amplitude of 318 km s$^{-1}$ is 12 km s$^{-1}$ greater than found by Courteau & van den Bergh (1999), because we include 14 additional galaxies, 5 of them dwarfs around M31 which turn out to have negative velocities larger than any previously known. Although we now have 40 galaxies for the analysis, they are strongly clustered on the sky and in distance. If the sample is split between the 16 galaxies nearer than 500 kpc (the Milky Way companions) and the 24 more distant than 500 kpc (mostly the M31 subgroup), then the amplitude of the solar motion with respect to these separate samples varies by $\pm 20$ km s$^{-1}$ (342 and 299 km s$^{-1}$, respectively). The assigned error attempts to account for the effects of poor sampling. Bootstrap resampling gives errors less than half what we quote. The direction of the Sun’s motion with respect to the Local Group has small errors, because it is stabilized by the dominant component: the orbital motion of the Sun in the Galaxy.

Our solution provides the transform from the heliocentric rest frame, $V_{LG}$, to the Local Group rest frame, $V_{LG}$,

$$V_{LG} = V_{\odot} - 86\dot{e} + 305\dot{f} - 33\dot{z},$$
$$V_{LG} = V_{\odot} + 270\dot{X} - 52\dot{Y} + 159\dot{Z}.$$  

The largest component of this motion is due to the rotation of the Sun within the disk of the Milky Way. Feast & Whitelock

\footnote{S. Courteau (2007, private communication) points out a misprint in his paper with van den Bergh; they intended to report $V_{\odot}^{\prime} = 306$ km s$^{-1}$ toward $\ell = 99$, $b = -3$.}
(1997) claim that the angular velocity at the solar position is $27.19 \pm 0.87 \text{ km s}^{-1} \text{ kpc}^{-1}$ and review the details of the local motion of the Sun, while Eisenhauer et al. (2005) report a distance to the Galactic center of $R_0 = 7.62 \pm 0.32$ kpc. The resultant transform of velocities from the solar to the Galactic standard of rest is

$$V_{\text{GSR}} = V_{\odot} + 9.3\hat{x} + 218\hat{y} + 7.6\hat{z},$$  \hspace{1cm} (13)$$
corresponding to a motion of the Sun of $V_{\text{GSR}}^{\odot} = 219 \pm 12 \text{ km s}^{-1}$ toward $\ell = 87.6, b = +2.0$ ($L = 356, B = +50$). Then the motion of the Galaxy within the Local Group is

$$V_{\text{LG}}^{\odot} = V_{\text{LG}} - V_{\text{GSR}} = -95\hat{x} + 87\hat{y} - 41\hat{z},$$  \hspace{1cm} (14)$$
or $135 \pm 25 \text{ km s}^{-1}$ toward $\ell = 137 \pm 10, b = -18 \pm 10$ ($L = 342, B = -3$). This direction is $17^\circ$ removed from the position of M31, offset toward the Maffei–IC 342 Group. The projected

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**Fig. 2.—** Peculiar velocities from two views, SGX vs. SGZ (left) and SGY vs. SGZ (right), in velocity units, for $H_0 = 70$ (top), 75 (middle), and 80 (bottom) km s$^{-1}$ Mpc$^{-1}$. Large symbols: Distances determined from Cepheids, TRGB, or SBF. Small symbols: Distances determined by the correlation between luminosity and line width. Black dots: No distance available. Red: Peculiar velocities away from us. Blue: Peculiar velocities toward us. An accompanying mpeg animation is available in the electronic edition of the Journal.
positions of these features are shown in Figure 3. The offset of the vector of our motion from M31 is sufficiently uncertain that a direct hit on M31 is not precluded.  

This Local Group rest frame may not deserve much attention. Within this rest frame the Milky Way has a motion of 135 km s\(^{-1}\), essentially toward M31, while M31 has a motion of zero toward us. With respect to the center of mass of the Local Group, in the absence of other forces, the Milky Way and M31 will have motions of approach that partition the observed 135 km s\(^{-1}\) in proportion to their masses. The evidence from the motions of satellites suggests that the two systems have comparable masses (Evans & Wilkinson 2000). Based on their relative luminosities, M31 could be expected to be 50% more massive. Certainly, the Milky Way is not a negligible test particle compared with M31. The so-called Local Group rest frame is essentially the M31 rest frame.

In the next section we will investigate a more useful frame of reference.

3.3. Peculiar Velocities within the Local Sheet

It is at this second step that things get interesting. Figure 4 zooms in from Figure 2 (now for the case \(H_0 = 74 \text{ km s}^{-1} \text{ Mpc}^{-1}\)) to highlight the local neighborhood. The color coding of velocities is more detailed. We see a remarkable discontinuity in peculiar velocities between the galaxies that lie in our filament and the regions just beyond. In the Nearby Galaxies Atlas (Tully & Fisher 1987), the structure we live in is called the Coma-Sculptor Cloud, because it creates a band from Galactic north pole to Galactic south pole. Our neighbors are tightly confined to the equatorial plane of the supergalactic coordinate system, and so fall within the slice only \(\pm 1.5 \text{ Mpc}\) thick about SGZ = 0 shown in Figure 5. The structure we live in and that has now been reasonably sampled with accurate distances has comparable dimensions in SGX and SGY. This region is not quite synonymous with the Coma-Sculptor Cloud, so we will refer to it as the “Local Sheet.”
The nearest adjacent structure lies in a layer at negative SGZ with respect to the Local Sheet and in the Nearby Galaxies Atlas is called the Leo Spur. The abrupt step in peculiar velocities at the edge of the Local Sheet was called the "local anomaly" by Faber & Burstein (1988), and we called that step in conjunction with the apparent motion toward us of the Leo Spur the "local velocity anomaly" (Tully 1988a; Tully et al. 1992). The large number of good TRGB distances available today place the local velocity anomaly in glaring relief.

The motion of the Local Group within the Local Sheet can be determined by realizing the minimization of equation (7) for \( N = 158 \) galaxies with measured distances in the range \( 1.1 < d_i < 7 \) Mpc; that is, beyond those in the Local Group and nearer than those in the adjacent structures. The best fit is found with \( H = 67 \) km s\(^{-1}\) Mpc\(^{-1}\) and a motion of the Local Group of \( 66 \pm 24 \) km s\(^{-1}\) toward \( L = 150 \pm 37, B = +53 \pm 20 \) (\( \ell = 349, b = +22 \)). This motion differs from zero with only marginal significance and is consistent with the observation by Karachentsev et al. (2003) that nearby groups and individual isolated galaxies adhere to the local expansion with a dispersion of only 40 km s\(^{-1}\). Note that the local expansion need not be, and is probably not, the same as the cosmic expansion.

The very low relative peculiar velocities within the Local Sheet and our small, marginally significant peculiar motion within this structure suggest that we consider a frame of reference that is at rest with respect to this structure. The motion of the Sun with respect to 158 galaxies with accurate distances at \( 1.1 < d_i < 7 \) Mpc in the Local Sheet defines the following relations:

\[
V_{\text{LS}} = V_\odot - 26\hat{x} + 317\hat{y} - 82\hat{z}, \tag{15}
\]

\[
V_{\text{LS}} = V_\odot + 234\hat{X} - 31\hat{Y} + 214\hat{Z}, \tag{16}
\]

or a motion of the Sun of \( V_\odot = 318 \pm 20 \) km s\(^{-1}\) toward \( \ell = 95 \pm 4, b = -1 \pm 4 \) (\( L = 353, B = +42 \)).\(^5\) The distance constraints are from Cepheid and TRGB methods and equally weighted.

---

\(^5\) The best fit is found with the local expansion term \( H = 67 \) km s\(^{-1}\) Mpc\(^{-1}\).

Rigorously, there should be a velocity correction to the centroid of the reference frame by the term \((H_0 - H) \times d_{\text{centroid}} \approx 10\) km s\(^{-1}\).
This direction is shown in Figure 3. It is seen to be close in amplitude and direction with $V_{LG}$. In fact, it is as close to our value of $V_{LG}$ as our value is to other estimates of the Local Group motion given in the literature. Given both the uncertainties in $V_{LG}$ and the ambiguity in the meaning of this reference frame, we will base the rest of our discussion on the rest frame established by galaxies beyond the Local Group but within 7 Mpc, velocities we designate $V_{LS}$. This reference frame is established by a completely independent sample from those that define $V_{LG}$ and is more robust, based on 5 times more galaxies and with good sky coverage.

3.4. The Velocity Discontinuity beyond the Local Sheet

The availability of TRGB distances to objects beyond the Local Sheet have strongly confirmed the existence of a velocity discontinuity at $\sim$7 Mpc. The effect is unambiguously seen in the nearest part of the Leo Spur at large negative supergalactic latitudes. The 14+19 association of dwarf galaxies (Tully et al. 2006) involves four galaxies with well-established distances ($7.8 \pm 0.3$ Mpc) and velocities ($195 \pm 26$ km s$^{-1}$ in the Local Sheet frame). The derivation of peculiar velocities requires an assumption of the value of the Hubble constant and, as will be justified later, we take $H_0 = 74$ km s$^{-1}$ Mpc$^{-1}$. In this case, members of the 14+19 association have peculiar velocities of $-382 \pm 47$ km s$^{-1}$. In addition, two companions of NGC 2903, D564-08, and D565-06, have reliable TRGB distances of 8.4 and 8.5 Mpc and velocities of 385 and 394 km s$^{-1}$, respectively, which imply peculiar velocities of $-237$ and $-235$ km s$^{-1}$, and there is the extreme case of the relatively isolated Leo Spur galaxy D634-03 at 9.3 Mpc with $V_{LS} = 186$ km s$^{-1}$ and $V_{pec} = -502$ km s$^{-1}$ (Karachentsev et al. 2006). These new high-precision distances to galaxies with significant SGZ components in the line of sight confirm what had earlier been suspected: that the Leo Spur and our Local Sheet have peculiar motions of several hundred km s$^{-1}$ toward each other. The peculiar motions of these galaxies in the line of sight are indicated in Figure 6.

It is evident from the peculiar velocity patterns in Figure 2 that the anomaly is not restricted to the Leo Spur. Negative peculiar velocities are seen all over in the region around the Virgo Cluster near the +SGY axis and generally at all $\pm$SGZ. The negative peculiar velocities in the direction of the Virgo Cluster have long been seen as a reflex of the pull of the cluster on us (Aaronson et al. 1982). This is part of the story, but not all of it. Another general feature is the trend of positive peculiar velocities in the quadrant with $+\text{SGZ}$ and $-\text{SGY}$.

The occurrence of the velocity anomaly is manifested in an abrupt break in the amplitude and direction of galaxy motions relative to our motion found through the condition imposed by equation (7). The vector of our relative motion can be determined in shells of either distance or velocity to look for systematic drifts that would be indicative of the depth of perturbations or for erratic bounces that would indicate instability in the solution. It is found that the vector of our motion is quite stable, achieving a direction and amplitude in the immediate shells beyond 7 Mpc that changes very little out to $V_{LS} \sim 3000$ km s$^{-1}$. The global solution over this range with $N = 683$ distance measures after averaging in groups provides the solution for transformation from Local Sheet referenced motions $V_{LS}$ to a reference frame established from objects within the general region of the Local Supercluster, $V_{LSC}$:

$$V_{LSC} = V_{LS} - 211\hat{x} - 178\hat{y} + 169\hat{z}$$  

(17)
Fig. 7.—Aitoff projection of observed peculiar velocities. Blue symbols: \( V_{\text{pec}} < -100 \text{ km s}^{-1} \); red symbols: \( V_{\text{pec}} > +100 \text{ km s}^{-1} \). The Local Sheet has a motion with respect to this sample toward the orange cross labeled LSC, and a motion toward the apex of the cosmic microwave background dipole at the position of the cyan cross labeled CMB. The heavy blue line defines the plane of our Galaxy. The knot of blue symbols at \( L = 103, B = -2 \) is the Virgo Cluster.

Fig. 8.—Motion within the Local Supercluster in the rest frame of the Local Group. Galaxies with \(-2000 < SGX < 2000 \text{ km s}^{-1}\) are plotted. Peculiar velocities are color coded as in Fig. 4. The vectors emanating from our position at the origin indicate our motion relative to these galaxies. They are described in Fig. 9, which is an enlargement of the central region of this figure.
Fig. 9.—Motion within and around our home structure, the Local Sheet, with $-500 < \text{SGX} < 1000 \text{ km s}^{-1}$. The orange vector represents $V_{LSC}^{LSK}$ with an amplitude of $323 \text{ km s}^{-1}$ in the rest frame of the Local Sheet. The blue vector has an amplitude of $185 \text{ km s}^{-1}$ and is directed toward the Virgo Cluster at the right edge of the figure. The red vector is the residual of these two, called $V_{LSC,LV}^{LSK}$, and has an amplitude of $259 \text{ km s}^{-1}$.

Fig. 10.—Region of the Local Void. The ellipses outline the three apparent sectors of the Local Void. The solid dark blue ellipses show two projections of the Inner Local Void, bounded on one edge by the Local Sheet. The North and South extensions of the Local Void are identified by the light blue short-dashed ellipses and the green long-dashed ellipses, respectively. These separate sectors are separated by bridges of wispy filaments. The red vector indicates the direction and amplitude of our motion away from the void.
or

\[
V_{\text{LSC}} = V_{\text{LS}} + 35\hat{X} + 196\hat{Y} - 255\hat{Z}.
\]

With respect to the general Local Supercluster reference frame, the Local Sheet has a motion of \(V_{\text{LS}}^{\text{LSC}} = 323 \pm 25 \text{ km s}^{-1}\) toward \(\ell = 220 \pm 7, b = +32 \pm 6 (L = 80, B = -52)\). This best solution is achieved with \(H_0 = 74 \text{ km s}^{-1} \text{ Mpc}^{-1}\). The solution is remarkably insensitive to the choice of \(H_0\). Variations from 60 to 90 km s\(^{-1}\) Mpc\(^{-1}\) result in variations in the velocity amplitude of only \(\pm 2 \text{ km s}^{-1}\) and variations in direction of only \(\pm 5^\circ\). With a choice of \(H_0\) less than 74 there is an overall expansion, and with \(H_0\) greater than 74 there is an overall compression. The value of \(H_0 = 74\) is accepted for the rest of the discussion, although it rests on the weak hypothesis that there is neither expansion nor compression centered on our location.

Figure 7 provides a display of the currently available sample of peculiar velocities in an equal-area projection on the sky. Galaxies with \(|V_{\text{pec}}| < 100 \text{ km s}^{-1}\) are not shown, in order to make clear the separation on the sky between galaxies with large positive peculiar velocities and those with large negative values. The crosses in the figure labeled LSC and CMB indicate vectors of motion that will be discussed in later sections. In the following discussion, the volume beyond 7 Mpc and with \(V_{\text{LS}} < 3000 \text{ km s}^{-1}\) sample, \(V_{\text{LS}}^{\text{LSC}} = 323 \text{ km s}^{-1}\) toward \(L = 80, B = -52\). The blue and red vectors are the residuals of the black vectors after vector addition of the component of the orange vector in their lines of sight (blue: residual toward our position; red: residual away from our position). In the case of the isolated galaxy ESO 461-36 in the Local Void, the components add to a velocity of 349 km s\(^{-1}\) toward us in the Local Supercluster reference frame.

A significant component of the peculiar motion of the Local Sheet comes from the pull of matter in and near the Virgo Cluster. The cluster itself has a mass approaching \(1 \times 10^{15} M_\odot\) (Mohayaee & Tully 2005). Numerical action method models demonstrate that this much mass in the cluster and a comparable amount of mass in the north Galactic hemisphere within the Local Supercluster generates a peculiar motion of \(\sim 200 \text{ km s}^{-1}\) in the Virgo direction at our location—as has long been implicated (e.g., Aaronson et al. 1982). The vector representing the motion of the Local Sheet with respect to the Local Supercluster, \(V_{\text{LS}}^{\text{LSC}}\), has a component directed toward the Virgo Cluster of \(V_{\text{LS}}^{\text{LSC,V}} = 185 \pm 20 \text{ km s}^{-1}\). If this vector toward Virgo is subtracted off the vector toward the overall Local Supercluster, the result is the vector \(V_{\text{LV}}^{\text{LSC,LV}}\), where LV stands for Local Void for reasons that will soon be described. Coordinate frame transforms obey

\[
V_{\text{LV}} = V_{\text{LS}} - 222\hat{X} - 130\hat{Y} - 10\hat{Z},
\]

\[
V_{\text{LV}} = V_{\text{LS}} + 77\hat{X} + 16\hat{Y} - 248\hat{Z},
\]
corresponding to a Local Sheet motion of $259 \pm 25$ km s$^{-1}$ toward $\ell = 210 \pm 7$, $b = -2 \pm 6$ ($L = 11$, $B = -72$). Since the Virgo and LV vectors are almost orthogonal, the decomposition has only a weak dependence on the amplitude of the Virgo component. A variation of $\pm 50$ km s$^{-1}$ in velocity toward Virgo affects $V_{LV}$ at the level of $10$ km s$^{-1}$ in amplitude and 15° in direction. The direction of the motion $V_{LSC}$ is shown in Figures 8 and 9, along with the decomposition vectors $V_{LSC;V}$ and $V_{LSC;LV}$.

3.5. The Local Void

The vector defined by equations (19) and (20) is not pointing at anything prominent, but it is directed away from the Local Void. This negative feature was identified in the Nearby Galaxies Atlas. The possible influence of the Local Void on our motion has been anticipated (Faber & Burstein 1988; Lahav et al. 1988). There is the claim that the far side of the void is in expansion away from us (Iwata et al. 2005). The significance of the Local Void has been difficult to evaluate because it is intersected by the zone of obscuration, but the neutral hydrogen survey HIPASS substantiates its importance (Meyer et al. 2004).

Figure 10 attempts a visualization of the Local Void. This absence of galaxies begins at the edge of the Local Group at positive SGZ. It appears to consist of a void within larger voids; minor filaments separate a smaller void from a larger almost empty region. We lie on a filament that serves as a wall for both the smaller and larger voids. Even the smaller void is not so small, with a long dimension of $\sim 35$ Mpc. The geometry of the larger enclosing void is quite uncertain. It appears to be bisected by a filament into north and south parts. The long dimension may be as large as 5000 km s$^{-1}$/70 Mpc. In the entire region, but especially with the larger component, aspects of the voids are poorly defined because of interruption by the zone of obscuration (roughly coincident with SGY = 0). The near and split far underdense regions will be referred to as the Inner, North, and South Local Voids, or in the ensemble as just the Local Void.

Motions on the far walls of the Local Void are poorly documented because of their distance and problems caused by obscuration. Current distance estimates for galaxies at 25–30 Mpc bounding the Local Void have peculiar velocities $\sim 300$ km s$^{-1}$. For the moment, these distances do not have sufficient quality to distinguish peculiar motions at the far wall of the Local Void from the reflex of the motion of the Local Sheet.

The Local Void being a void, there is not much opportunity to measure motions within the void, but we are offered at least one
chance. An HST observation provides a TRGB measurement for the lonely galaxy ESO 461-36 = KK 246 (Karakchentsev et al. 2006). The distance given in that reference is probably too great, primarily because the reddening estimate that was used (Schlegel et al. 1998) is too low. Using the procedures described by Rizzi et al. (2007), we find a distance of 6.4 Mpc. Although closer than previously suspected, the galaxy still lies well into the Local Void. This galaxy has an observed \( V_{\text{LS}} = 443 \text{ km s}^{-1} \), resulting in \( V_{\text{pec}} = -30 \text{ km s}^{-1} \) with \( H_0 = 74 \). However, ESO 461-36 is at almost the opposite pole from the Local Sheet motion described by equations (17) and (18). Its motion with respect to the Local Supercluster is roughly the sum of our motion and its additional motion in the same direction (discounting proper motion components). Hence, this galaxy is trying to escape from the void with a deviant velocity of at least 350 km s\(^{-1}\). The situation is seen in Figure 11. ESO 461-36 has a peculiar velocity toward us in the Local Sheet rest frame, as do galaxies on almost the opposite side of the sky in the Leo Spur. However, in the rest frame established by galaxies with known distances in the Local Supercluster, we are moving toward the Leo Spur and away from ESO 461-36. With respect to the LSC, ESO 461-36 has a very high peculiar velocity.

Figure 11 provides more details than Figure 6 concerning the motions of galaxies below the supergalactic equatorial plane. All the galaxies indicated in the plot lie in the Leo Spur and have accurately known distances and systemic velocities. Assuming \( H_0 = 74 \text{ km s}^{-1} \text{ Mpc}^{-1} \), all galaxies in this sector have substantial peculiar velocities toward us. The average motion for the 10 good cases in the figure is \(-335 \text{ km s}^{-1}\) in the Local Sheet rest frame. On cancellation of the motion of the Local Sheet with respect to the Local Supercluster, the average residual for these 10 galaxies is \(-34 \text{ km s}^{-1}\), with a standard deviation of 29 km s\(^{-1}\). To within the errors, velocities in the Leo Spur can be viewed as simply the reflex of our motion in that direction. We should be reminded, however, of the continuing uncertainty in the parameter \( H_0 \). The average residual for these 10 galaxies would be nil if the assumed value of the Hubble constant is reduced by \( \Delta H = -3 \). By the same token, the residual would be significant if \( \Delta H > +3 \).

Returning nearer to home, we can ask if there is a gradient of peculiar velocity with SGZ within the Local Sheet. We look for this possibility with Figure 12. The distance from the supergalactic equatorial plane is plotted against peculiar velocity. Galaxies inside and outside the filament are distinguished by color and symbol shape. The general trend of negative velocities can be interpreted as an overall local retardation from the mean cosmic expansion. The largest negative \( V_{\text{pec}} \) are seen in the Leo Spur. Restricting attention to the galaxies within \( \pm 1.5 \) Mpc of the plane of our filament, one finds a marginal offset in peculiar velocities between positive and negative SGZ: \( \langle V_{\text{pec}} \rangle_{\text{SGZ} < 0} = -33 \pm 10 \text{ km s}^{-1} \) for 80 cases and \( \langle V_{\text{pec}} \rangle_{\text{SGZ} > 0} = 0 \pm 13 \text{ km s}^{-1} \) for 54 cases, a difference of \( 33 \pm 16 \text{ km s}^{-1} \).

The flare of galaxies at \( -5 < \text{SGZ} < 1.5 \) Mpc off the Local Sheet seen in Figure 12 is a minor feature that includes NGC 1313 and intrinsically smaller galaxies. For 14 cases, \( \langle V_{\text{pec}} \rangle_{\text{flare}} = -63 \pm 12 \text{ km s}^{-1} \). These galaxies are moving toward positive SGZ with respect to the Local Sheet. However, in the LSC frame they are moving toward negative SGZ, like us but not as rapidly.

3.6. The Large-Scale Component of Our Peculiar Velocity

The Local Supercluster motion expressed by equations (17) and (18) fails in both amplitude and direction to explain the motion indicated by the cosmic microwave background. The principal sources of that motion are suspected to lie at distances in velocity of 3000–6000 km s\(^{-1}\) (Lynden-Bell et al. 1988; Erdogdu et al. 2006a) if not out at 10,000–15,000 km s\(^{-1}\) (Scaramella et al. 1989; Kocevski & Ebeling 2006). The sample of distances used in this paper reaches only to the inner edge of the nearer of these domains. Perturbations consistent with the large-scale flows discussed by others (Tonry et al. 2000) are seen at the edge of our field of study at large –SGX. The Centaurus Cluster with \( V_{\text{LS}}^\text{cen} = 3152 \text{ km s}^{-1} \) at \( d^\text{cen} = 37 \text{ Mpc} \) has \( V_{\text{pec}}^\text{cen} = +429 \text{ km s}^{-1} \) if \( H_0 = 74 \text{ km s}^{-1} \text{ Mpc}^{-1} \).

To a first approximation, the local and large-scale components of our motion can be treated as decoupled. Let us determine the properties of the large-scale component upon subtraction of the
local component from the CMB vector. The transform between our Local Sheet frame and the reference frame of the CMB (Fixsen et al. 1996) is given by

\[ V_{\text{CMB}} = V_{\text{LS}} + \mathbf{v}_{\text{LS}} + \mathbf{v}_{\text{CMB}} \]

which describes a motion of the Local Sheet of \( 631 \pm 20 \) km \( \text{s}^{-1} \) toward \( \ell = 270 \pm 3, b = +27 \pm 3 \) \( (L = 139, B = -37) \). Subtraction of the Local Supercluster motion of equations (17) and (18) from the CMB motion,

\[ V_{\text{CMB}} - V_{\text{LSC}} = +212 \hat{x} - 385 \hat{y} + 116 \hat{z} \]

\[ V_{\text{CMB}} - V_{\text{LSC}} = -416 \hat{x} + 135 \hat{y} - 125 \hat{z} \]

describes a motion of \( 455 \pm 15 \) km \( \text{s}^{-1} \) toward \( \ell = 299 \pm 3, b = +15 \pm 3 \) \( (L = 162, B = -16) \). The vector of motion of the Local Sheet indicated by the CMB dipole, \( V_{\text{CMB}} \), and the residual to this vector after the locally generated component \( V_{\text{LS}} \) is subtracted off are shown in Figure 13. The direction of this large-scale component is closely aligned with the Norma-Hydra-Centaurus supercluster complex and background Shapley concentration, lying within 7° of the direction of the Centaurus Cluster.

There is a recapitulation of the various reference frames and vectors in Table 3, and Figure 14 provides a visual summary. The projected locations of the various vectors are indicated on this plot. The CMB vector can be decomposed into the vector determined by motions within 3000 km \( \text{s}^{-1} \) (the Local Supercluster component) and a residual attributed to structure on large scales.
The Local Supercluster component can be decomposed in turn into the components toward the Virgo Cluster and away from the Local Void.

It is known that the distribution of various populations of galaxies peak in roughly the direction of the CMB dipole maximum. Two recent studies are considered here. Erdogdu et al. (2006a) have calculated the dipole in the distribution of sources brighter than $K_s = 11.25$ from the Two-Micron All-Sky Redshift Survey (2MRS). Kocevski & Ebeling (2006) have made the equivalent determination based on the distribution of X-ray-selected clusters of galaxies. These alternatively derived dipole directions are plotted in Figure 14. In both cases, these dipole directions are midway between the CMB and Local Supercluster vector directions. It is inferred that the 2MRS dipole is determined relatively locally.

The particular interest in this study is the influence of the Local Void on our motion. First, however, a few words are in order that the direction of the X-ray dipole is pulled from the CMB direction toward the direction of the large-scale component of our motion.

The 2MRS sample is attractive because redshifts are available for almost all the galaxies. This information can be used to construct dynamical models (Erdogdu et al. 2006b). However, if mass is distributed like light, then since both luminosity and gravity diminish as the square of distance, the net attraction on the Galaxy should be described by the full, deep 2MASS sample, without recourse to redshifts. The analysis by Maller et al. (2003) produced a dipole that moves from the 2MRS position 22° west of the CMB position to 8° west in Galactic longitude. The Maller et al. dipole position is 15° north of the CMB position in Galactic latitude, but this displacement may be due to the way the mask of the obscured region of the Galactic plane is filled. This is the region of the Local Void. If the region of the Local Void were given far fewer sources in the Maller et al. mask, the full 2MASS dipole would be pushed close to the CMB target. It can be noted that the 2MRS analysis uses more information at low Galactic latitudes and gets a closer fit to the CMB in latitude (although as mentioned, this shallower survey gets a worse fit in longitude).

4. DISCUSSION

In future, the database of galaxy distances and peculiar velocities will be used for detailed studies of the distribution of matter using nonparametric numerical action methods (Shaya et al. 1995), techniques that can be used on small scales and at high densities. For the moment, the discussion is restricted to first-order effects. It has been emphasized that the motion of the Local Sheet reflected in the CMB dipole can be decomposed into three main components. Of course, this is a simplification, and taken to the other extreme of complexity this motion can be broken into an arbitrarily large number of influences.

The 2MASS dipole from the 2MRS lies midway between the CMB and Local Supercluster vector directions. It is inferred that the 2MRS dipole is determined relatively locally.
Fig. 15.—X-ray and near-infrared dipole amplitudes. Top: The solid blue line shows the development of the number-weighted X-ray cluster dipole amplitude with redshift. The dashed red line shows the equivalent information for 2 μm selected sources. Bottom: Histograms of the redshift distributions of the X-ray and 2 μm selected samples. [See the electronic edition of the Journal for a color version of this figure.]
regarding the other two principal components. Concerning scales larger than 3000 km s$^{-1}$, we would only point out here that a larger local contribution to the CMB motion implies a smaller value of $\beta = \Omega_m^{0.6}/b$ as derived from the amplitude of the dipole of large-scale features. Here, $\Omega_m$ is the mean density of matter compared with the density of matter that would give a closed universe, and $b$ is the bias between the distribution of matter and the distribution of observable tracers. For example, the values of $\beta$ calculated by Kocevski & Ebeling (2006) from the X-ray cluster sample, which has the dependence $\beta = V_{pec}/D_{cl}$, where $D_{cl}$ is the dipole amplitude found from the X-ray clusters, is reduced by the lower large-scale component of $V_{pec}$ found here by 11% from the values given by Kocevski & Ebeling.

The component of our motion attributed to inflow toward the Virgo Cluster was discussed by Mohayaee & Tully (2005). This component is particularly amenable to modeling by numerical action methods with the large number of distance constraints that are becoming available. We reserve further discussion for another paper, but emphasize the relative decoupling from the motion away from the Local Void because (1) the two components are almost orthogonal, and (2) the scale of the Virgo Cluster influence is governed by the cluster distance of 17 Mpc, while there are sharp gradients attributed to Local Void effects on scales of only a few Mpc.

4.1. Expansion of Voids

We turn now to consider the reflex motion from the Local Void. First, what can be expected on theoretical grounds? The Friedmann equation can be written as

$$H^2 = \left(\frac{a}{a_0}\right)^2 = \frac{8\pi G \rho}{3} + \frac{\Lambda}{3} - \frac{K}{a_0^2} c^2 + \frac{\rho_m}{a_0^2} c^2,$$

(25)

where $a$ is the radial scale factor normalized to $a = 1$ today, and the three terms on the right describe contributions from the mean density of matter, $\rho$, the vacuum energy, $\Lambda$, and spatial curvature, $K$. Within a completely empty void,

$$\dot{a}^2 = \left(\frac{\Lambda}{3}a^2 - Kc^2\right).$$

(26)

This expression can be related to global parameters with $\alpha = H_e/H_0$, where $H_e = \dot{a}/a$ inside the void and $\Omega_\Lambda = \Lambda/3H_0^2$:

$$\dot{a} = H_e \left(\frac{\Lambda a^2}{3H_0^2} - \frac{Kc^2}{H_0^2}\right)^{1/2} \text{;}$$

(27)

then since the curvature term in the void is

$$-\frac{Kc^2}{H_0^2} = 1 - \frac{\Lambda}{3H_0^2},$$

(28)

we arrive at

$$\dot{a} = \alpha H_0 \left(\frac{\Omega_\Lambda a^2}{\alpha^2} + \left(1 - \frac{\Omega_\Lambda}{\alpha^2}\right)^{1/2}\right).$$

(29)

We solve for the value of $\alpha$ that takes $a$ from 0 to 1 in time $t_0$ for the case $\Omega_m = 0.24$, $\Omega_\Lambda = 0.76$, $H_0 = 74$ km s$^{-1}$ Mpc$^{-1}$, and $t_0 = 13.7$ Gyr. We find $\alpha = 1.22$, which gives an expansion in the void relative to the universal flow of

$$H_e - H_0 = 16 \text{ km s}^{-1} \text{ Mpc}^{-1}. \quad \text{(30)}$$

For comparison, with $\Omega_m = 0.3$, $\Omega_\Lambda = 0.7$ one finds $\alpha = 1.25$ and $H_e - H_0 = 18 \text{ km s}^{-1}$.

These values are in good agreement with results from simulations reported by van de Weygaert & Schaap (2007). Those simulations show that in models with $\Lambda = 0$ the voids are not fully evacuated at the present epoch, and motions out of voids are consequently lower than if the voids were empty. However, in the simulations with $\Omega_\Lambda \sim 0.7$ the voids are quite empty at $z = 0$, suggesting that we can give serious consideration to this possibility in the case of the Local Void. Figure 16 illustrates the dependence of outflow velocities on the residual density within a void for two cosmological models.

In § 3.4 it was determined that the Local Sheet has a bulk motion of 259 km s$^{-1}$ away from the Local Void. Simplistically, it could be inferred that the radius of a completely empty Local Void is at least 16 Mpc.

It is not out of the question that the entire Local Void, including the Inner, North, and South components, could have this dimension. The geometry of the Local Void is poorly delineated because of the unfortunate intersection of the plane of the Milky Way. Certainly, this region is not entirely empty. Several wispy filaments lace through the volume. If the void is not empty, then a larger size is required to generate the observed expansion velocities.

We can raise a couple of layers of complexity. Recovery of velocity fields from simulations provide a guide. Figure 17 is extracted from van de Weygaert & Schaap (2007). The example we show involves the reasonably symmetric convergence of material onto a filament. Streaming motions grow approximately linearly away from the centers of the low-density regions on each
side of the filament, reaching maxima at the interface with the filament. This behavior is consistent with expectations based on the formulae given above. However, although particles impinging on the filament have large velocities in the example seen here, the filament does not have a large lateral bulk motion. In this particular case, there is considerable symmetry with the influx from the opposite sides of the filament. In other circumstances, there might be an asymmetry. An example is provided by Figure 18. The sequence of 4 time steps is drawn from an N-body GADGET simulation (Springel 2005) produced by the HORIZON collaboration.\(^6\) Attention is drawn to a filament that has the combined properties seen in the Local Sheet of lateral motion due to the dominance of a void on one side and a flow toward a nearby cluster in an orthogonal direction. Two adjacent filaments displace laterally toward convergence, reproducing the behavior seen between the Local Sheet and the Leo Spur.

The observed motion of ESO 461-36 gives a useful constraint. This dwarf galaxy is still well within the Local Void, still within the unfettered flow toward our filament. With reference to the flow pattern seen in the lower right panel of Figure 17, a galaxy such as ESO 461-36 might be anticipated to be near the maximum of the swing of peculiar velocities. We measure a peculiar velocity for this galaxy of \(-30\) km s\(^{-1}\). As was noted in § 3.5, this motion is additive with our velocity in the reference frame of the Local Supercluster, which implies a peculiar velocity of at least \(350\) km s\(^{-1}\) with respect to that reference frame. The peculiar velocity is higher if the galaxy has a significant tangential component. This galaxy should have a motion of \(~120\) km s\(^{-1}\) due to the influence of the Virgo Cluster, leaving an additional \(~230\) km s\(^{-1}\) attributable to evacuation from the void. Equation (30) requires that ESO 461-36 be at least 17 Mpc from the void center. Since we are 6 Mpc farther back, that would put us 23 Mpc from the void center. Maybe so. However, this requires that the void be very big and very empty. The situation invites consideration of more radical alternatives. Dutta & Maor (2007) argue that dark energy with a varying equation of state might have enhanced density in places with lower mass density; i.e., in voids. One consequence could be an enhanced expansion rate of space in voids, resulting in increased velocities away from void centers. Potentially, observations of the motions of galaxies within voids could give

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\(^6\) See http://www.projet-horizon.fr/article323.html.
important information about the fundamental properties of the universe.

5. SUMMARY

Our motion inferred by the CMB dipole anisotropy of 631 km s\(^{-1}\) in the Local Sheet reference frame decomposes into three main contributions that are almost orthogonal. The three main components conveniently lie near the cardinal axes of the Supergalactic coordinate system (only partially by chance). Two of these components decouple from the third, because two are local, the closest seen abruptly in a peculiar velocity discontinuity at 7 Mpc, while the third is large-scale, acquiring an importance at \(v_{LS} > 3000\) km s\(^{-1}\).

One of the local components is caused by the Virgo Cluster and its dense surroundings. The motion of the Local Sheet with respect to galaxies within 3000 km s\(^{-1}\) has a component of 185 km s\(^{-1}\) toward this cluster at \(L = 103, B = -2\). The residual from the local component of CMB motion is a Local Sheet velocity of 259 km s\(^{-1}\) toward \(L = 11, B = -72\), toward nothing of importance but away from the Local Void. Subtraction of these two local components from the CMB vector leaves the third component, attributed to large-scale attractors, of 455 km s\(^{-1}\) toward \(L = 162, B = -16\), close to the direction of the Centaurus Cluster. These three components cause motions roughly aligned with the +SGY, −SGZ, and −SGX axes, respectively, providing a decomposition that is gruntling.

The availability of a large number of accurate TRGB distances has clarified details about the “local velocity anomaly.” Our Local Sheet is participating in the cosmic expansion (although probably somewhat retarded), but simultaneously moving in bulk toward the Virgo Cluster and away from the Local Void. Our Local Group has only a small peculiar velocity (66 km s\(^{-1}\)) with respect to other galaxies of the Local Sheet which, internally, has only small random motions (40 km s\(^{-1}\) in the radial direction averaged over groups). We advocate the use of the Local Sheet as a frame of reference in preference to the Local Group because the reference sample is 5 times larger and more widely distributed. The local velocity anomaly is given emphasis, because there is a sharp discontinuity in velocities as we look beyond the Local Sheet toward −SGZ. Galaxies in the Leo Spur with well-measured distances all have large negative peculiar velocities. Most, if not all, of these motions are a reflex of the motion of the Local Sheet toward −SGZ and away from the Local Void.

Our distances are not yet numerous or accurate enough to demonstrate whether other filaments have similar bulk motions. However, we do see clearly that a galaxy within but near our edge of the Local Void, ESO 461−36, has a peculiar velocity of at least 230 km s\(^{-1}\) away from the center of the void. Our Local

![Figure 18](http://example.com/fig18.png)

**Fig. 18.**—Four snapshots in time of an N-body simulation with conditions resembling the observations. The dark matter GADGET simulation is of a 20 Mpc box with 256\(^3\) particles, ΛCDM, with \(Ω_m = 0.3\) and \(Ω_Λ = 0.7\). The region shown is 10 Mpc across in comoving coordinates at the redshift steps \(z = 1, 0.5, 0.25,\) and 0. The skeleton method (Sousbie et al. 2008) delineates the backbone of the filaments at each step. The large circle in each panel identifies the progression of a location that ends up with properties resembling those of the Milky Way: on a filament, with motions that are both lateral to the filament away from a void, and along the filament toward a cluster. The large triangle in each panel tracks a location that comes to resemble the Leo Spur, with upward motions headed toward a future closure with the filament bearing the circle. An accompanying mpeg animation is available in the electronic edition of the Journal.
Sheet and that galaxy are participating in the evacuation of the Local Void. The large explosion velocities imply a dimension of the radius to the center of the Local Void at our position of at least 23 Mpc. We lie on the boundary of a major void. The evidence for expansion is unambiguous at our privileged position on the void wall. Voids have few galaxies, but are they really empty? Yes, to create such a large outflow, our Local Void must be really empty.

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