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THE SOLAR MOTION RELATIVE TO THE LOCAL GROUP

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ABSTRACT

New data on the membership of the Local Group (LG) are used, in conjunction with new and improved radial velocity data, to refine the derivation of the motion of the Sun relative to the LG. The Sun is found to be moving with a velocity of $V = 306 \pm 18$ km s^{-1} toward an apex at $l = 99° \pm 5°$ and $b = -4° \pm 4°$. This finding agrees very well with previous analyses, but we discuss the possibility of a bias if the phase-space distribution of LG galaxies is bimodal. The LG radial velocity dispersion is 61 ± 8 km s^{-1}. We use various mass estimators to compute the mass of the LG and the Andromeda subgroup. We find $M_{\rm LG} = (2.3 \pm 0.6) \times 10^{12}\ M_\odot$, from which $M/L_V = 44 \pm 12$ (in solar units). For an assumed LG age of 14 ± 2 Gyr, the radius of an idealized LG zero-velocity surface is $r_0 = 1.18 \pm 0.15$ Mpc. The LG is found to have 35 likely members. Only three of these have (uncertain) distances $\gtrsim 1.0$ Mpc from the LG barycenter. Barring new discoveries of low surface brightness dwarfs, this suggests that the LG is more compact and more isolated from its surroundings than previously believed.

Key words: galaxies: clusters: general — galaxies: kinematics and dynamics — galaxies: spiral — Local Group

1. INTRODUCTION

The motion of the Sun relative to the other members of the Local Group (LG) has been studied for many decades, with investigations by Humason, Mayall, & Sandage (1956), Yahil, Tammann, & Sandage (1977, hereafter YTS77), Sandage (1986), Karachentsev & Makarov (1996), and Rauzy & Gurzadyan (1998 and references therein; hereafter RG98). YTS77 and many others have stressed the importance of understanding the solar motion relative to the LG in the context of the large-scale motions of galaxies. The reliability of measurements of peculiar motions in the universe, or residual motion from the uniform Hubble expansion, depends in part on accurate knowledge of the motion of the solar system relative to any standard inertial frame. This inertial rest frame is usually taken as the centroid of the Local Group of galaxies or the reference frame in which the dipole of the cosmic microwave background (CMB) vanishes (Kogut et al. 1993). The motion of the Sun relative to the CMB can be decomposed into a sum of local and external components:[1]

$$V_{\rm Sun \to CMB} = V_{\rm Sun \to LSR} + V_{\rm LSR \to GSR} + V_{\rm GSR \to LG} + V_{\rm LG \to CMB} . \quad (1)$$

$V_{\rm Sun \to LSR}$ is the motion of the Sun relative to the nearby stars that define a local standard of rest (LSR), and the motion $V_{\rm LSR \to GSR}$ is the circular rotation of the LSR about the Galactic center, which is directed toward $l = 90°$ and $b = 0°$. Externally, $V_{\rm GSR \to LG}$ is the motion of the Galactic center (or Galactic standard of rest) relative to the LG centroid, which is caused by nonlinear dynamics within the LG (mostly infall of the Galaxy toward M31). Finally, $V_{\rm LG \to CMB}$ is the peculiar velocity of the LG in the CMB rest frame, induced by gravitational perturbations in the universe.

Recent discoveries of new candidate members of the LG, and the deletion of former candidates, have allowed us to revise the solution for the solar motion relative to the LG, $V_{\rm Sun \to LG}$, to assess Group membership, and to compute a new value for the mass of the LG. Three criteria are usually invoked to assess the probability that a galaxy is associated with the LG: (1) The distance to that galaxy from the LG barycenter should be less than (or comparable to) the radius at the zero-velocity surface (Lynden-Bell 1981; Sandage 1986), (2) the galaxy should lie close to the ridgeline solution between radial velocity and the cosine of the angle from the solar apex relative to well-established LG members, and (3) it should not appear to be associated with any more distant group of galaxies centered well beyond the limits of the LG. We examine these criteria below.

This paper is organized as follows: First, in § 3, we compute a new solution for the motion of the Sun relative to LG members. Then in § 4 we estimate the radius of the zero-velocity surface, and we assess LG membership in § 5, based on the three criteria listed above. We conclude in § 6 with a brief discussion and summary and a digression on the detectability of small groups like the LG using X-ray telescopes.

Recent studies of the membership in the LG also include van den Bergh (1994a, 1994b), Grebel (1997), and Mateo (1998). The reader is referred to van den Bergh (2000, hereafter vdB2000) for a comprehensive review of the nature of the LG and the question of membership in it.

2. DATA

A listing of information on the 32 probable (and three possible) members of the LG that were isolated using the criteria discussed above is given in Table 1. Columns (1)–(3) give the names and David Dunlap Observatory morphological types (van den Bergh 1966, 1994b) for each LG member. Equatorial (J2000.0) and Galactic coordinates are listed in columns (4)–(7). Various photometric parameters taken from vdB2000 (visual color excess, absolute visual magnitude, and true distance modulus) are listed in columns (8)–(10). Column (11) gives the heliocentric radial velocity of each galaxy in kilometers per second, and column (12) lists the cosine of the angle between each galaxy and the solar motion apex in the rest frame of the LG.

[1] Our notation is analogous to that of RG98.

TABLE 1

OBSERVATIONAL DATA ON LOCAL GROUP MEMBERS

Name (1)	Alias (2)	DDO Type (3)	R.A. (4)	Decl. (5)	l (deg) (6)	b (deg) (7)	$E(B-V)$ (8)	M_V (9)	DM (10)	V_r (km s^{-1}) (11)	cos θ (12)	d (Mpc) (13)	d_{LG} (Mpc) (14)	Ref. (15)
WLM	DDO 221	Ir IV–V	00 01 57.8	−15 27 51	75.852	−73.626	0.02	−14.4	24.85	−120	0.317	0.93	0.79	1
IC 10	UGC 192	Ir IV:	00 20 24.5	59 17 30	118.973	−3.341	0.85:	−16.3	24.10	−344	0.940	0.66	0.27	2
NGC 147	UGC 326	Sph	00 33 11.6	48 30 28	119.816	−14.253	0.17	−15.1	24.10	−193	0.919	0.66	0.22	3
And III..........	A0032+36	dSph	00 35 17.0	36 30 30	119.313	−26.250	0.05	−10.2	24.40	...	0.866	0.76	0.31	
NGC 185	UGC 396	Sph	00 38 58.0	48 20 18	120.792	−14.482	0.19	−15.6	24.10	−202	0.912	0.66	0.22	3
NGC 205	M110	Sph	00 40 22.5	41 41 11	120.718	−21.138	0.04	−16.4	24.40	−244	0.887	0.76	0.31	4
M32	NGC 221	E2	00 42 41.9	40 51 55	121.151	−21.976	0.06	−16.5	24.40	−205	0.880	0.76	0.31	2
M31	NGC 224	Sb I–II	00 42 44.2	41 16 09	121.174	−21.573	0.06	−21.2	24.40	−301	0.882	0.76	0.30	5
And I............	A0043+37	dSph	00 45 43.0	38 00 24	121.690	−24.851	0.04	−11.8	24.55	...	0.861	0.81	0.36	
SMC		Ir IV/IV–V	00 52 36.0	−72 48 00	302.812	−44.328	0.06	−17.1	18.85	148	−0.611	0.06	0.48	6
Sculptor		dSph	01 00 04.3	−33 42 51	287.686	−83.157	0.00	−9.8	19.70	110	−0.057	0.09	0.44	7
Pisces............	LGS 3	dIr/dSph	01 03 56.5	21 53 41	126.770	−40.884	0.03	−10.4	24.55	−286	0.707	0.81	0.42	8
IC 1613		Ir V	01 04 47.3	02 08 14	129.730	−60.558	0.03	−15.3	24.30	−232	0.474	0.72	0.47	9
And V		dSph	01 10 17.1	47 37 41	126.220	−15.123	0.16	−10.2	24.55	...	0.873	0.81	0.37	
And II............		dSph	01 16 29.8	33 25 42	128.918	−29.152	0.08	−11.8	24.22	...	0.785	0.70	0.26	
M33	NGC 598	Sc II–III	01 33 50.9	30 29 37	133.648	−31.494	0.07	−18.9	24.50	−181	0.732	0.79	0.37	10
Phoenix		dIr/dSph	01 51 03.3	−44 27 11	272.193	−68.949	0.02	−9.8	23.00	...	−0.299	0.40	0.59	
Fornax		dSph	02 39 53.1	−34 30 16	237.245	−65.663	0.03	−13.1	20.70	53	−0.252	0.14	0.45	11
LMC		Ir III–IV	05 19 36.0	−69 27 06	280.187	−33.287	0.13	−18.5	18.50	275	−0.801	0.05	0.48	12
Carina............		dSph	06 41 36.7	−50 57 58	260.112	−22.223	0.05	−9.4	20.00	223	−0.851	0.10	0.51	13
Leo A	DDO 69	Ir V	09 59 23.0	30 44 44	196.903	52.410	0.02	−11.5	24.20	24	−0.132	0.69	0.88	14
Leo I	Regulus	dSph	10 08 26.7	12 18 29	225.980	49.108	0.02	−11.9	22.00	287	−0.439	0.25	0.61	15
Sextans...........		dSph	10 13 02.9	−01 36 52	243.498	42.272	0.04	−9.5	19.70	226	−0.642	0.09	0.51	16
Leo II	DDO 93	dSph	11 13 27.4	22 09 40	220.142	67.229	0.03	−10.1	21.60	76	−0.256	0.21	0.57	17
Ursa Minor......	DDO 199	dSph	15 08 49.2	67 06 38	104.884	44.901	0.03	−8.9	19.00	−247	0.661	0.06	0.43	18
Draco	DDO 208	dSph	17 20 18.6	57 55 06	86.370	34.708	0.03	−8.6	19.50	−293	0.766	0.08	0.43	18
Milky Way	Galaxy	S(B)bc I–II	17 45 39.9	−29 00 28	359.944	−0.046	...	−20.9:	14.65	16	−0.157	0.01	0.46	19
Sagittarius		dSph(t)	18 55 04.3	−30 28 42	5.610	−14.090	0.15	−13.8::	17.00	142	−0.042	0.03	0.46	20
Sag DIG[a]		Ir V	19 29 58.9	−17 40 41	21.056	−16.285	0.07	−10.7:	25.70	−79	0.217	1.40:	1.48	21
NGC 6822.......		Ir IV–V	19 44 56.0	−14 48 06	25.338	−18.392	0.25	−16.0	23.50	−56	0.286	0.50	0.67	2
Aquarius[a]	DDO 210	V	20 46 53.0	−12 50 58	35.112	−30.932	0.03	−11.3	25.05	−131	0.408	1.02	1.02	22
Tucana[a]		dSph	22 41 48.9	−64 25 21	322.906	−47.366	0.00	−9.6	24.70	...	−0.442	0.87	1.10	
Cassiopeia	And VII	dSph	23 26 31.0	50 41 31	109.464	−9.946	0.17	−9.5	24.20	...	0.977	0.69	0.29	
Pegasus	DDO 216	Ir V	23 28 34.0	14 44 48	94.768	−43.547	0.15	−12.3	24.40	−182	0.763	0.76	0.44	2
Pegasus II	And VI	dSph	23 51 39.0	24 35 42	106.013	−36.305	0.04	−10.6	24.60	...	0.834	0.83	0.43	

NOTE.—Units of right ascension are hours, minutes, and seconds, and units of declination are degrees, arcminutes, and arcseconds (J2000.0).

[a] Possible LG member.

REFERENCES.—(1) de Vaucouleurs et al. 1991; (2) RC3; (3) Bender, Paquet, & Nieto 1991; (4) Peterson & Caldwell 1993; (5) van den Bergh 2000; (6) Hardy, Suntzeff, & Azzopardi 1989; (7) Queloz, Dubath, & Pasquini 1995; (8) Young & Lo 1997; (9) Lake & Skillman 1991; (10) Deul & van der Hulst 1987; (11) Mateo et al. 1991; (12) Westerlund 1997, p. 28; (13) Mateo et al. 1993; (14) Young & Lo 1996; (15) Mateo 1998; (16) Suntzeff et al. 1993, Hargreaves et al. 1994; (17) Vogt et al. 1995; (18) Armandroff et al. 1995; (19) Delhaye 1965; (20) value for NGC 6715 adopted from Harris 1996; (21) Longmore et al. 1978; (22) Lo, Sargent, & Young 1993.

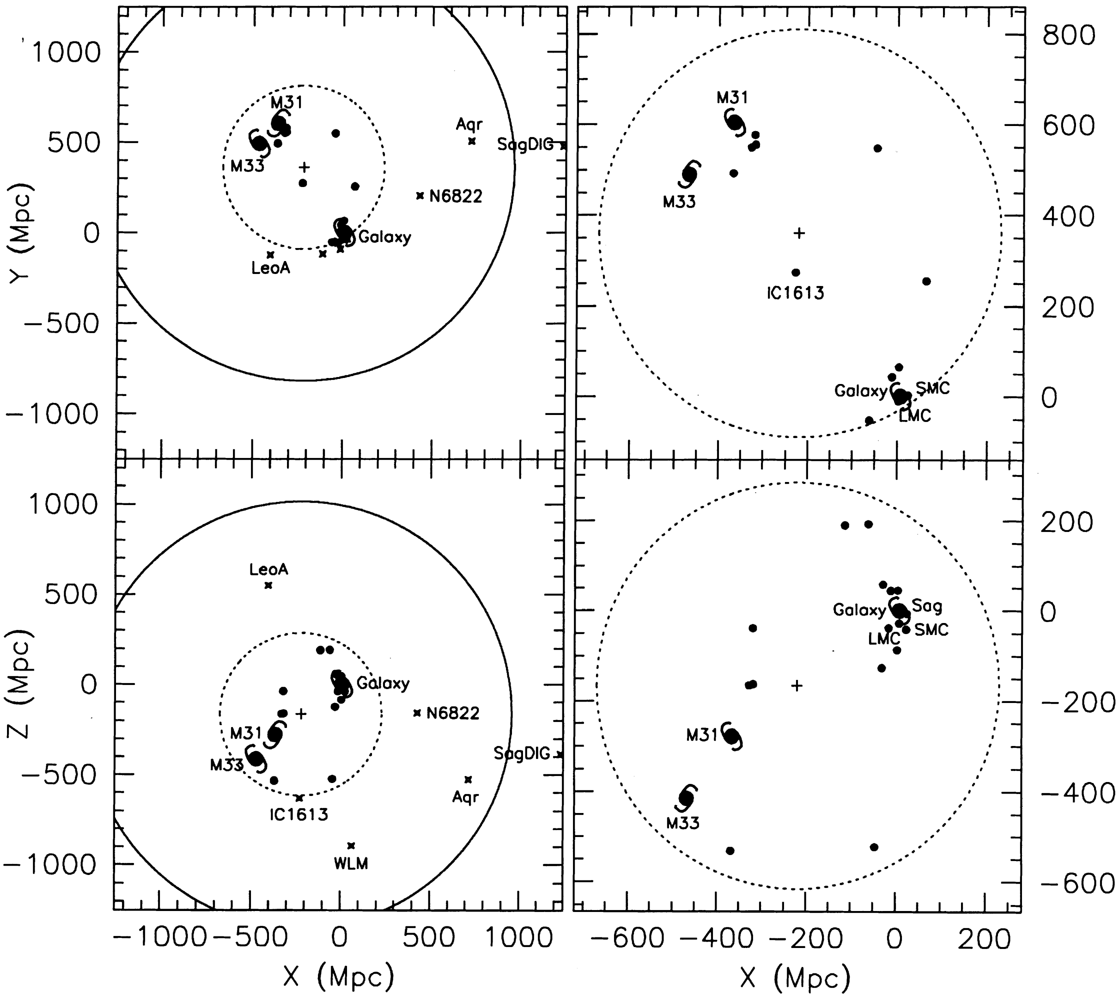

FIG. 1.—Positions of LG members in Galactic Cartesian coordinates, as viewed from two orthogonal directions. The left side shows a sphere of radius $r_0 = 1.18$ Mpc (corresponding to the zero-velocity surface of the LG) as a solid line. The dotted line shows a sphere of radius $r_h = 450$ kpc, which encompasses both the Andromeda and Galaxy subgroups. Both spheres are centered on the LG barycenter at $X = -220$, $Y = +361$, and $Z = -166$ kpc. For clarity, not all the LG members have been labeled. Filled circles represent galaxies within the Andromeda/Galaxy volume; LG members outside of this sphere are plotted as crosses. The Galaxy, M31, and M33 are shown with a spiral galaxy symbol.

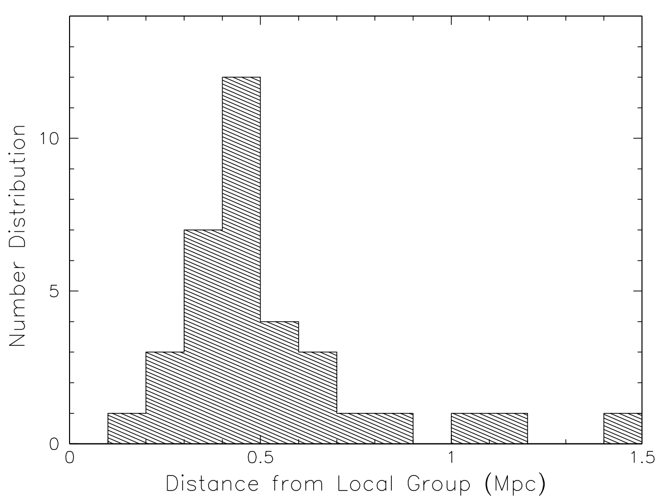

FIG. 2.—Histogram showing the distribution of measured distances of all known LG members from the LG dynamical center. It is seen that the membership drops steeply beyond $D_{\rm LG} \simeq 0.85$ Mpc. The density of galaxies near $D_{\rm LG} = 0$ is small because the center of the LG is situated between the Andromeda and Galactic subgroups, where few galaxies are found.

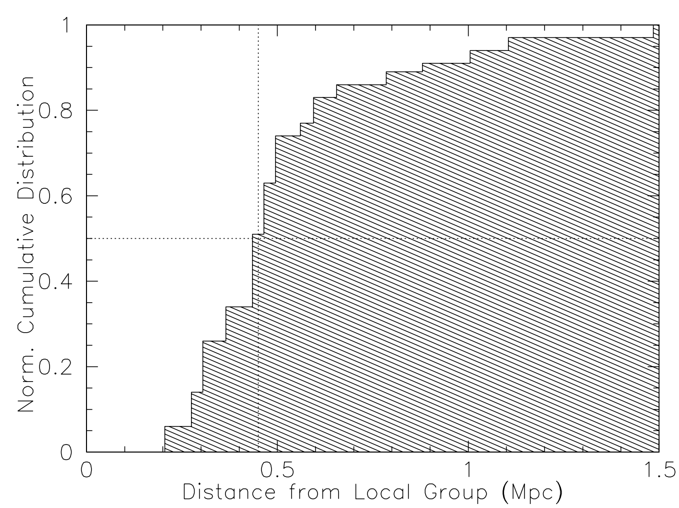

FIG. 3.—Cumulative distance distribution of all known LG members. This histogram shows that the core of the LG has $\lesssim 0.85$ Mpc. Half of the known members of the LG are seen to located within 450 kpc of the adopted barycenter.

Columns (13) and (14) give the distance of a galaxy from the Sun and from the LG barycenter in megaparsecs. Finally, column (15) gives the main reference to each of the radial velocities quoted in column (11). The LG suspects at large distances (footnoted in Table 1) are Aquarius (DDO 210), with a distance from the LG center of 1.02 ± 0.05 Mpc (Lee 1999), Tucana, at $\simeq 1.10 \pm 0.06$ Mpc (vdB2000), and Sag DIG, with a poorly determined LG distance of 1.20 Mpc $\lesssim D \lesssim$ 1.58 Mpc (Cook 1987). Uncertain entries in Table 1 are followed by a colon.

The positions of LG members in Cartesian Galactocentric coordinates are shown in Figure 1. The velocity components, X, Y, Z, of an object point toward the Galactic center ($l = 0°$, $b = 0°$), the direction of Galactic rotation ($l = 90°$, $b = 0°$), and the north Galactic pole ($b = +90°$), respectively.

We have calculated distances of individual galaxies relative to the LG barycenter by (1) assuming that most of the LG mass is concentrated in the Andromeda and Galactic subgroups, (2) adopting a distance to M31 of 760 kpc (vdB2000), and (3) assuming that M31 is 1.5 times more massive than the Milky Way (Mateo 1998; Zaritsky 1999 and references therein). Lacking more detailed information about the mass constituents of the LG, it seems reasonable to expect that the local center of mass will be situated on the line between our Galaxy and M31 in the direction of M31. The LG barycenter is located at 0.6 times the distance to M31, at 454 kpc toward $l = 121°.7$ and $b = -21°.3$. In Galactic Cartesian coordinates this corresponds to $X = -220$, $Y = +361$, and $Z = -166$ kpc.

Histograms of the differential and cumulative distance distributions of the LG members relative to its barycenter are shown in Figures 2 and 3, respectively. These figures show that all probable LG members have distances $\lesssim 850$ kpc from the dynamical center of the LG. Taken at face value, this suggests that the core of the LG may be smaller and more isolated from the field than has generally been assumed (e.g., Jergen, Freeman, & Bingelli 1998; Pritchet 1998).

3. SOLAR MOTION RELATIVE TO LOCAL GROUP MEMBERS

Using the line-of-sight velocities and positions of probable LG members (Table 1), we compute a new solution for the bulk motion of the Sun relative to the LG centroid. The computation of a bulk flow $\boldsymbol{v}^B$ is independent of estimated distances to any of the galaxies, or the exact shape of their orbits, provided that the spatial and velocity distributions are independent (see, e.g., YTS77; RG98). If the three-dimensional velocity distribution is invariant under spatial translations, one can further assume that the global velocity field can be decomposed into the sum of a bulk flow $\boldsymbol{v}^B$ and a three-dimensional random isotropic Maxwellian distribution with a velocity dispersion σ_v. The bulk flow statistics reduces to the maximization of the likelihood function

$$\mathscr{L} = -\ln \sigma_v - \frac{1}{N} \sum_{k=1}^{N} \frac{(v_r^k - v_x^B \hat{r}_1^k - v_y^B \hat{r}_2^k - v_z^B \hat{r}_3^k)^2}{2\sigma_v^2} , \quad (2)$$

where v_r^k is the observed radial velocity of galaxy k and the components $\{\hat{r}_j^k\}_{j=1,2,3}$ are the direction cosines of that galaxy. The inferred solar apex corresponds to the direction that minimizes scatter in the distribution of radial velocities versus $\cos \theta$, where θ is the angle between the solar apex and the unit vector toward each galaxy.

Details on such techniques and confidence in the estimators can be found in YTS77 and RG98 (our estimator is identical to that developed by RG98). The observational errors in the radial velocities are relatively small, and they are insignificant compared with the residual velocity dispersion. They are therefore neglected. Here we adopt the values quoted by the main source in column (15) of Table 1. Standard deviations for the amplitude and direction of the solar motion and for the residual velocity dispersion of the LG are estimated by bootstrap resampling of the input data (these are also available from the Hessian matrix of second derivatives). The errors quoted correspond to the 1 σ dispersion for each parameter.

A maximum likelihood solution, giving equal weight to all 26 objects with measured heliocentric radial velocities, yields a solar motion with $V_\odot = 306 \pm 18$ km s^{-1} toward an apex at $l = 99° \pm 5°$ and $b = -3° \pm 4°$. The residual radial velocity dispersion in the LG is $\sigma_r = 61 \pm 8$ km s^{-1}. Assuming the velocity distribution of LG galaxies to be isotropic, the three-dimensional velocity dispersion in the LG is $\simeq 106$ km s^{-1}.

A comparison with other published solutions for the motion of the Sun relative to the LG barycenter is given in Table 2. With the exception of RG98, most solutions are found to be in agreement with each other to within their quoted errors. For example, our solution seldom differs by more than 1 km s^{-1} from YTS77, with a maximum deviation of ± 2 km s^{-1}.

The good agreement among most published solutions is not fortuitous. The dynamics of the LG are heavily dominated by systems that were already included in the sample of Mayall (1946, the earliest reference cited here). The addition of new members, especially to the Galaxy subgroup (which now accounts for half of all known LG members with a measured redshift), has not altered the solar motion solution in any significant way. Moreover, most studies of solar motion relative to LG galaxies have assumed a

TABLE 2

SOLAR MOTION RELATIVE TO THE LOCAL GROUP

$V_\odot$ (km s^{-1})	l (deg)	b (deg)	References
306 ± 18	99 ± 5	−3 ± 4	This paper
305 ± 136......	94 ± 48	−34 ± 29	RG98
316 ± 5	93 ± 2	−4 ± 2	Karachentsev & Makarov 1996
295	97	−6	Sandage 1986
308 ± 23	105 ± 5	−7 ± 4	YTS77
315 ± 15	95 ± 6	−8 ± 3	de Vaucouleurs & Peters 1968
292 ± 32	106 ± 6	−7 ± 4	Humason & Wahlquist 1955
308 ± 26	93 ± 6	−14 ± 4	Mayall 1946

uniform potential that governs LG dynamics. The solar motion amplitude measured by Sandage (1986) assumes a two-to-one mass ratio between M31 and our Galaxy. A lower mass ratio of 1.5, as we advocate here, would yield an even lower amplitude.

The result by RG98 differs more substantially from all others because of the different nature of their approach. As a first step, RG98 recognize the existence of the two main dynamical substructures within the LG, namely, the Galaxy subgroup (13 galaxies)[2] and the Andromeda subgroup (seven galaxies). For each subgroup, RG98 estimate a bulk flow using equation (2). They find, in Galactocentric coordinates, $\boldsymbol{V}_{\text{Galsub}\to\text{Sun}} = (94 \pm 64, \ -354 \pm 42, \ 37 \pm 33)$ km s^{-1}, or $|\boldsymbol{V}_{\text{Galsub}\to\text{Sun}}| = 368 \pm 28$ km s^{-1} toward ($l = 285° \pm 11°$, $b = +6° \pm 5°$), and $\boldsymbol{V}_{\text{Andsub}\to\text{Sun}} = (-127 \pm 541, -143 \pm 267, 301 \pm 254)$ km s^{-1}, or $|\boldsymbol{V}_{\text{Andsub}\to\text{Sun}}| = 357 \pm 218$ km s^{-1} toward ($l = 228° \pm 180°$, $b = +58° \pm 65°$). The error bars for the bulk flow estimate of the Andromeda subgroup are large because of the small number of galaxies involved in the statistics, and because of the narrow angular size of the subgroup on the sky (i.e., bulk flow components perpendicular to the M31 line of sight are poorly constrained). RG98 compute the global bulk flow of the LG as the mean motion of its main dynamical substructures, equally weighted, i.e., $\boldsymbol{V}_{\text{LG}\to\text{Sun}} = (\boldsymbol{V}_{\text{Galsub}\to\text{Sun}} + \boldsymbol{V}_{\text{Andsub}\to\text{Sun}})/2$, which yields $\boldsymbol{V}_{\text{LG}\to\text{Sun}} = (-17 \pm 303, \ -249 \pm 155, \ 169 \pm 144)$ km s^{-1}, or $|\boldsymbol{V}_{\text{LG}\to\text{Sun}}| = 301$ km s^{-1} toward ($l = 266°$, $b = +34°$). The residual velocity dispersion is $\sigma_r = 110.3$ km s^{-1}. Error bars are thus larger in RG98's treatment because of the poor estimate of the M31 subgroup's bulk flow.

RG98 suggest that the phase-space distribution of LG galaxies is bimodal. Application of bulk flow statistics from equation (2) to a uniform LG distribution may therefore be biased. Indeed, with the exception of RG98, the results quoted in Table 2 apply if the velocity distribution function of selected LG galaxies is the sum of a three-dimensional bulk flow, plus a random component that does not correlate with the spatial position of galaxies. However, solar motion solutions that assume a uniform three-dimensional structure for the LG may be biased if the Andromeda subgroup bulk flow $\boldsymbol{V}_{\text{Andsub}\to\text{Sun}}$ differs significantly from that of the Galaxy subgroup $\boldsymbol{V}_{\text{Galsub}\to\text{Sun}}$.

This suggestion is supported by RG98's analysis and corroborated by our own reexamination of this issue. Our analysis, based on equation (2), also suggests that the Andromeda subgroup would partake of a different, stronger bulk motion than the Galaxy subgroup. But, given the large errors in the apex parameters of the Andromeda subgroup, it would be premature to make any claims based on these results. In any case, the poor number statistics do not allow a rejection or confirmation of this hypothesis. All solutions that account for subgrouping or a uniform structure of the LG agree to within their 1 σ confidence interval.

3.1. *Summary of Corrections to Radial Velocities*

The correction to heliocentric radial velocities V_{hel} for a solar apex of direction (l_a, b_a) and amplitude V_a in any reference frame can be expressed as

$$V_{\text{corr}} = V_{\text{hel}} + V_a[\cos b \cos b_a \cos(l - l_a) + \sin b \sin b_a] , \quad (3)$$

where l and b are the Galactic coordinates to the observed galaxy. The peculiar motion of the Sun relative to the LSR is 16.5 km s^{-1} toward $l = 53°$ and $b = +25°$ (Delhaye 1965; see also Crampton 1968), or $X = +9$, $Y = +12$, and $Z = +7$ km s^{-1} (note the typographical error in eq. [1] of Braun & Burton 1999). Therefore,

$$V_{\text{LSR}} = V_{\text{hel}} + 9 \cos l \cos b + 12 \sin l \cos b + 7 \sin b . \quad (4)$$

The Galactic rotation has an amplitude $Y = 220 \pm 20$ km s^{-1} ($X = 0$, $Z = 0$) toward $l = 90°$ and $b = 0°$ (IAU 1985 convention; see Kerr & Lynden-Bell 1986). Therefore, the corrected radial velocity of a galaxy in the Galactic standard of rest is

$$V_{\text{GSR}} = V_{\text{hel}} + 9 \cos l \cos b + 232 \sin l \cos b + 7 \sin b . \quad (5)$$

The corrections given above are widely used and accepted (de Vaucouleurs et al. 1991, hereafter RC3). We also found (see § 3) the correction for motion of the Sun relative to the LG centroid as

$$V_{\text{LG}}(\text{this paper}) = V_{\text{hel}} - 79 \cos l \cos b + 296 \sin l \cos b - 36 \sin b , \quad (6)$$

under the assumption that the velocity distribution function in the LG can be described as bulk flow plus a random isotropic Maxwellian component. Applying the same premises, not to the LG as a whole as we did, but to the two main LG substructures, RG98 find (see also Table 2)

$$V_{\text{LG}}(\text{RG98}) = V_{\text{hel}} - 18 \cos l \cos b + 252 \sin l \cos b - 171 \sin b . \quad (7)$$

The RC3 does not include any corrections for galaxy motions in the frame of the LG, on account of their ill-defined nature. This was perhaps a wise decision. De Vaucouleurs et al. (1976, hereafter RC2) report the "old" solar apex solution (300 sin l cos b), but modern solutions (Table 2) show deviations from the RC2 formulation as large as ± 87 km s^{-1}, as already noted by YTS77. Perhaps even more important are the deviations that exist between our solution and that of RG98. The maximum deviations (eqs. [6], [7], and [8]) are ± 154 km s^{-1} toward ($l = 145°$, $b = +60°$) and ($l = 325°$, $b = -60°$). These are shown in Figure 4, with negative and positive residuals represented by stars and circles, respectively.

In choosing a reference frame for cosmological studies, one may transform heliocentric radial velocities to the CMB frame (e.g., Kogut et al. 1993). Under the assumption that the CMB dipole is kinematic in origin, and not the product of any external force field, this operation carries little uncertainty. On the other hand, the transformation to the LG rest frame is free of any assumptions about the origin of the CMB dipole and minimizes the effect of the mass distributed outside the sample. Modern solutions for solar motion with respect to LG galaxies that assume a uniform LG potential and a fixed LG barycenter are robust. These studies yield nearly identical solutions (e.g., Table 2). However, this result can be due either to the homogeneous nature of the LG or to the fact that we are making similar erroneous assumptions. The kinematic method described above can lead to biased results if the phase-space galaxy distribution is not homogenous. The use of a dynamical

[2] RG98's "Milky Way" subgroup does not include the newly discovered Sagittarius dwarf spheroidal.

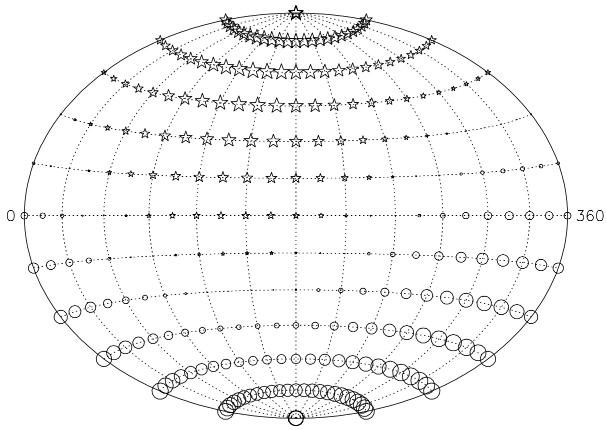

FIG. 4.—Aitoff projection in Galactic coordinates showing the residuals between our solution for the solar motion relative to the LG (eq. [6]) and that of RG98 (eq. [7]). The size of the symbols is linearly proportional to the magnitude of the residual, the largest ones being $+154$ km s^{-1} in the direction ($l = 145°$, $b = +60°$), and -154 km s^{-1} toward ($l = 325°$, $b = -60°$). Positive and negative residuals (this paper; RG98) are shown with circles and stars, respectively.

method to reconstruct the orbits of individual LG galaxies could provide a potentially more accurate description of the motion of the LG center of mass. Such a method, based on least-action principles, has been proposed (Shaya, Peebles, & Tully 1995), but it depends on a reliable knowledge of the galaxy distribution outside the LG, which is lacking at present. Clearly, it is the prerogative of the astronomer to adopt (and justify) whatever cosmological rest frame he or she prefers.

Given that the mean motion of the LG is consistent with the combined motion of its two main substructures, we will adopt the "standard" solution (eq. [6]) as the best description of solar motion relative to the LG. However, one should keep in mind the main caveats/assumptions for this solution, as we reiterate in § 6.

4. MASS OF THE LOCAL GROUP

If we assume that the LG is in virial equilibrium and that its velocity ellipsoid is isotropic ($\sigma^2 = 3\sigma_r^2$), then the mass of the LG can be computed from its velocity dispersion (Spitzer 1969; see also Binney & Tremaine 1987, eqs. [4]–[80b]) as

$$M_{\rm LG} \simeq \frac{7.5}{G} \langle \sigma_r^2 \rangle r_h = 1.74 \times 10^6 \langle \sigma_r^2 \rangle r_h \; M_\odot \,, \quad (8)$$

where r_h is the radius in kpc containing half the mass as measured from the center of the isotropic distribution. The numerical value of r_h can be estimated from the cumulative distance distribution of LG members shown in Figure 2. We find that $r_h \sim 450$ kpc. This number-weighted figure is clearly an upper limit to the actual mass-weighted estimate. If M31 accounts for approximately 60% of the mass in the LG, a simple mass distribution model gives $r_h \simeq 350$ kpc. Using this value and $\sigma_r = 61 \pm 8$ km s^{-1}, we find $M_{\rm LG} = (2.3 \pm 0.6) \times 10^{12}\, M_\odot$.

It is of interest to tally the mass of individual LG components. To compute the mass of the Andromeda subgroup, we use the projected mass method of Bahcall & Tremaine (1981) and Heisler, Tremaine, & Bahcall (1985; see also Aceves & Perea 1999). In the absence of specific information on the distribution of orbital eccentricities, the projected mass estimator is given by

$$M_{\rm PM} = \frac{10.2}{G(N - 1.5)} \sum_i V_{zi}^2 R_i \,, \quad (9)$$

where R is the projected separation from M31 (assuming $D_{\rm M31} = 760$ kpc) and V_z^2 is the radial velocity in the frame of M31. Table 3 gives the relevant parameters for all seven known members of the Andromeda subgroup. We find that the Andromeda subgroup has a mass of $(13.3 \pm 1.8) \times 10^{11}\, M_\odot$, the lower and upper bounds corresponding to the virial and projected mass estimates, respectively, following the notation of Heisler et al. (1985).

From the inferred motion of nearby satellites, Zaritsky (1999) shows that the Galactic subgroup has a mass of $(8.6 \pm 4.0) \times 10^{11}\, M_\odot$. Thus, the two major subgroups have a combined mass of $(21.9 \pm 4.4) \times 10^{11}\, M_\odot$. This may be compared to the virial mass of $(23 \pm 6) \times 10^{11}\, M_\odot$ found above for the entire LG. This agreement may be fortuitous if the LG is not in virial equilibrium or if the LG potential is nonisotropic. However, taken at face value, this result suggests that most of the dark and luminous mass in the LG is locked into the Andromeda and Galactic subgroups, unless the intracluster dark matter is distributed in a highly flattened shape. The timing argument by Kahn & Woltjer (1959), which is based on the motion of the Galaxy toward M31, yields a minimum LG mass of about $18 \times 10^{11}\, M_\odot$. Sandage (1986), using a similar argument for the deceleration of nearby galaxies caused by the LG, finds a maximum mass for the LG equal to $5 \times 10^{12}\, M_\odot$, with a best-fit value of $4 \times 10^{11}\, M_\odot$. He also arrives at this low value by using the dispersion as a virial velocity to compute a virial mass for the LG. The formula he used for the virial mass differs by a factor of 7.5 from ours (eq. [8]), introduced by replacing $\sigma^2 = 3\sigma_r^2$ for an isotropic velocity ellipsoid and considering the half-mass radius, r_h, instead of the ill-defined gravitational radius r_g. Sandage also used an estimate for r_g that is too small by a factor of about 2 (if $r_h \simeq 0.4 r_g$). This explains the discrepancy "by a factor of 7" (compared with Kahn-Woltjer) discussed by Sandage. Moreover, his result, that $M_{\rm LG} = 4 \times 10^{11}\, M_\odot$ based on a velocity perturbation analysis of the LG, assumes a formation age of 18.1 Gyr ($H_0 = 55$ km s^{-1} Mpc^{-1} for an $\Omega = 0$

TABLE 3

THE ANDROMEDA SUBGROUP

Name	R[a]	$v_{\rm hel}$	$v_{\rm cor}$[b]	$q/(10^{11}\, M_\odot)$[c]
M32	5.3	−205	95	0.11
NGC 205	8.0	−244	58	0.06
NGC 185	93.9	−202	107	2.49
NGC 147	98.3	−193	118	3.18
M33	197.3	−181	72	2.37
IC 10	242.9	−344	−29	0.48
Pisces	263.0	−286	−38	0.90

[a] Projected separations in kpc are based on a distance to M31 of 760 kpc. Compare with Bahcall & Tremaine 1981, Table 4.

[b] Velocities $v_{\rm cor}$ in km s^{-1} are corrected for the solar motion relative to the local and Galactic standards of rest (eq. [5]) and for radial motion of the Galaxy toward M31, i.e., $v_{\rm cor} = V_{\rm GSR} + 124\,[\cos b \cos(-21.3) \cos(l - 121.7)] + \sin b \sin(-21.3)$.

[c] Projected mass $q \equiv v_z^2 R/G\, M_\odot$.

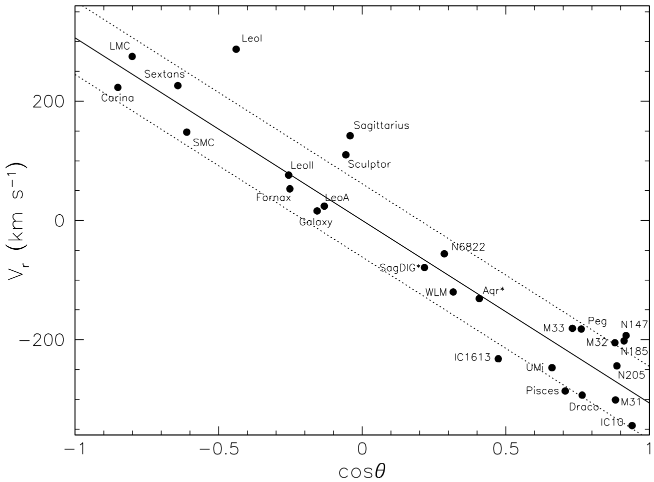

FIG. 5.—Observed heliocentric velocities V_r of LG members vs. cos θ, where θ is the angular distance from the solar apex. Our solar motion solution of 306 ± 18 km s^{-1} toward $l = 99° \pm 5°$ and $b = -3° \pm 4°$ is shown as the solid ridgeline. Dotted lines correspond to the residual radial velocity dispersion of ± 61 km s^{-1} from the ridge solution. Note the large deviations of Leo I and of the Sagittarius dwarf (which is strongly interacting with the Galaxy) from the mean motion of LG members.

universe) and that $M_{\rm M31} = 2M_{\rm Gal}$. Adoption of revised figures, $H_0 = 65$ km s^{-1} Mpc^{-1} and $M_{\rm M31} = 1.5M_{\rm Gal}$, yields a model-data comparison that agrees perfectly well with $M_{\rm LG} = (2.3 \pm 0.6) \times 10^{12}$ $M_\odot$ (see Sandage 1986, Fig. 11). Thus, both calculations in Sandage (1986) are consistent with a higher value for $M_{\rm LG}$, equal to the one we measure.

From the absolute magnitudes of LG galaxies listed in Table 1, we compute the total luminosity of the LG to be $L_V = 5.2 \times 10^{10}$ $L_\odot$,[3] corresponding to $M_V({\rm LG}) = -22.0$. Combined with our estimate of the virial mass and assuming a 10% error in L_V, we measure $M/L_V = 44 \pm 12$

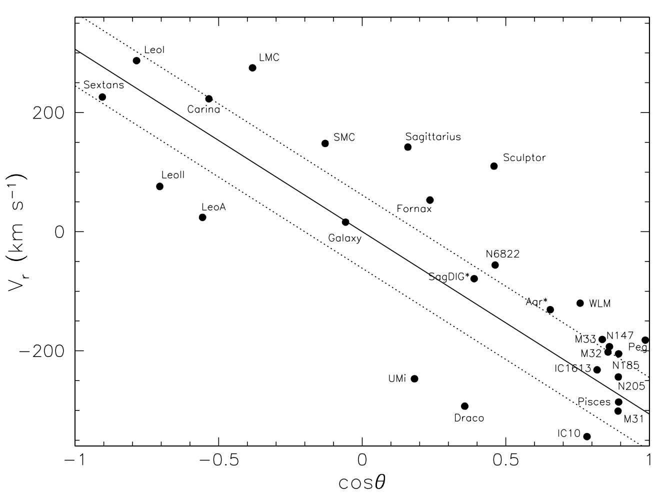

FIG. 6.—Same as Fig. 5, but using the solar motion solution of RG98 with $V_\odot = 306 \pm 18$ km s^{-1} toward $l = 94° \pm 48°$ and $b = -34° \pm 29°$. For comparison, the solid ridgeline and dotted dispersion lines are those computed for Fig. 5. Note that the dispersion around the regression relation of RG98 (eq. [7]) is twice larger ($\sigma_r = 110.3$ km s^{-1}) than that for the standard solution shown in Fig. 5.

[3] Adopting $M_{V\odot} = +4.82 \pm 0.02$ (Hayes 1983).

in solar units.[4] It is perhaps worth noting that M31 and the Galaxy together provide 86% of the luminosity of the LG. The uncertainty in M_V(Galaxy) and in M_V(M31) contributes significantly to the error of the integrated luminosity of the LG.

Finally, one can compute the radius of the zero-velocity surface, r_0, that separates Hubble expansion from cluster contraction at the present epoch (Lynden-Bell 1981; Sandage 1986). As the universe expands, the zero-velocity surface moves outward with time. If the total random components of the velocity field cancel out, one can write, from equation (7) of Sandage (1986),

$$r_0({\rm Mpc}) = \left(\frac{8GT^2}{\pi^2} M_{\rm LG}\right)^{1/3}$$
$$= 0.154T({\rm Gyr})M_{\rm LG}(10^{12}\ M_\odot)\ . \qquad (10)$$

Assuming that the age of the LG is 14 ± 2 Gyr, and using our estimate of the virial mass of the LG, we find $r_0 = 1.18 \pm 0.15$ Mpc. The value of r_0 given above can now be used to assess LG membership.

5. LOCAL GROUP MEMBERSHIP

On the basis of the membership criteria listed in § 1, van den Bergh (1994b) concluded that it was safe to exclude the following galaxies from membership in the LG: (1) the Sculptor irregular (=UKS 2323−326), (2) Maffei 1 and its companions, (3) UGCA 86 (=A0355+66), (4) NGC 1560, (5) NGC 5237, and (6) DDO 187. A particularly strong concentration of LG suspects, including objects 2, 3, 4, and 5 listed above, occurs in the direction of the IC 342/Maffei Group (van den Bergh 1971; Krismer, Tully, & Gioia 1995), which Krismer et al. place at a distance of 3.6 ± 0.5 Mpc. Cassiopeia 1, regarded as an LG suspect (Tikhonov 1996), also appears to be a member of the IC 342/Maffei Group. Van den Bergh & Racine (1981) failed to resolve LG suspect LGS 2 on large reflector plates. They conclude that this object is either a Galactic foreground nebula, or an unresolved stellar system at a much greater distance than that of M31 and M33. Another longtime LG suspect is DDO 155 (=GR 8). However, observations by Tolstoy et al. (1995) have resulted in the discovery of a single probable Cepheid, which yields a distance of 2.2 Mpc, so that this galaxy would lie outside of the LG boundary. The spiral galaxy NGC 55 has recently been listed as a possible LG member by Mateo (1998). However, it appears preferable to follow in the footsteps of de Vaucouleurs (1975), who assigns this galaxy to the Sculptor (South Polar) Group. Côté, Freeman, & Carignan (1994) show that NGC 55 is located close to the center of the distribution of dwarf galaxies associated with the South Polar Group. Furthermore, photometry in J, H, and K by Davidge (1998) shows that NGC 55, NGC 300, and NGC 7793 are located at comparable distances. Sandage & Bedke (1994, panel 318) write, "NGC 55 is very highly resolved into individual stars, about equally well as other galaxies in the South Polar Group such as NGC 247 and NGC 300. Evidently, NGC 55 is just beyond the Local Group." Finally, Jergen et al. (1998) place NGC 55 on the near side of the Sculptor Group. We have also excluded the galaxies NGC 3109, Antlia, Sextans A,

[4] Sandage (1986) finds $M/L \sim 25$ for $M_{\rm LG} \sim 3 \times 10^{12}$ $M_\odot$. His lower M/L estimate is based in part on a higher estimate for the total luminosity of the Local Group.

and Sextans B from membership in the LG. These objects, which have measured distances of 1.36, 1.33, 1.45, and 1.32 Mpc, respectively (vdB2000), are located relatively close together on the sky. Their mean distance from the barycenter of the LG, which is situated about 450 kpc away in the direction toward M31, is 1.7 Mpc. Furthermore, these galaxies have a mean redshift of 114 ± 12 km s^{-1} relative to the V_r–cos θ relation derived in § 3 (see vdB2000). These data suggest that NGC 3109, Antlia, Sextans A, and Sextans B form a physical grouping that is receding from LG and that lies just beyond the LG zero-velocity surface (van den Bergh 1999). We note that NGC 3109, Sextans A, and Sextans B were also excluded by YTS77 on the basis of their solar motion solutions. Zijlstra & Minniti (1999) find that the LG candidate IC 5152 is located at 1.8 ± 0.2 Mpc, which places it outside the LG zero-velocity surface.

Group membership can be revised by inspection of the V_r–cos θ diagram, which illustrates the motions of individual galaxies with respect to the ensemble of the galaxies in the Group. This is shown in Figure 5 for LG galaxies (see also Fig. 6). The LG radial velocity dispersion, $\sigma_r = 61 \pm 8$ km s^{-1}, is shown by dotted lines. Suspected outliers lying below the 1 σ regression line are few. None of the systems presented in Figure 5 can be excluded from membership on the basis of this test. The two blueshifted systems (IC 1613 and Pisces), and a handful of redshifted LG objects, fall within 2 σ of the regression line. Membership for many recently discovered dwarf spheroidals cannot be examined with this test, because their radial velocities are not yet available.

Figure 1 shows that most of the LG members are concentrated in subgroups that are centered on the Andromeda galaxy and on the Milky Way system. However, a few objects, such as NGC 6822, IC 1613, Leo A, and the WLM system, appear to be free-floating Group members. Aquarius (=DDO 210), Tucana, and Sag DIG are so far from the barycenter of the LG that their membership in the LG cannot yet be regarded as firmly established, even though they lie close to the solar ridgeline in the V_r–cos θ diagram.

It might be argued that our value of σ_r is biased low because the database may lack (unknown) nearby fast-moving galaxies. However, this effect is probably not important, because no galaxies are found with large blueshifts relative to the mean relationship between cos θ and apex distance.

6. DISCUSSION AND SUMMARY

We have measured a new solution for the solar motion relative to LG galaxies that agrees very well with previous derivations by, e.g., YTS77, Sandage (1986), and Karachentsev & Makarov (1996). Following RG98, it is worth pointing out that these solutions are only physically meaningful under the assumption that the three-dimensional spatial and velocity distributions are independent. This would not be true if the LG potential were bimodal. This is verified by computing the motion of the Sun relative to the two main LG substructures, the Andromeda and Galaxy subgroups, and testing whether their combined motion matches that inferred relative to the entire LG. Preliminary indications suggest that the Andromeda subgroup is moving faster with respect to the Sun and in a different direction from the Galaxy subgroup. However, the error bars (mostly for $V_{\rm Sun \rightarrow Andsub}$) are far too large to rule out the "standard" solution. Indeed, the combined subgroup solutions are perfectly consistent with our final derivation for the solar motion relative to all LG members with $V_{\rm Sun \rightarrow LG} = 306 \pm 18$ km s^{-1} toward an apex at $l = 99° \pm 5°$ and $b = -4° \pm 4°$. It is worth pointing out that interpretation errors for the solar motion may linger until we obtain a better understanding of the true orbital motions of LG members and a better knowledge of the overall distribution of mass in the LG.

The observed radial velocity dispersion of the LG is $\sigma_r = 61 \pm 8$ km s^{-1}. Braun & Burton (1999) measured a radial velocity dispersion $\sigma_r = 69$ km s^{-1} for the motion of intracluster compact H I high-velocity clouds (HVCs). Although close in dispersion to the LG value, HVCs exhibit an excess of infall velocities (blueshifts), suggesting that many of them may still be falling into the LG at present, contrary to bona fide LG galaxies.

Table 1 presents an updated listing of 35 probable members of the LG. Half of all the members are located within 450 kpc of the barycenter of the LG, with only three objects, Sag DIG, Aquarius, and Tucana, being more than 1 Mpc away. These results show that the (binary) core of the LG is relatively compact and well-isolated from other nearby clusters. This conclusion was already anticipated by Hubble in his *Realm of the Nebulae* (Hubble 1936, p. 125): "the Local Group is [a] typical, small group of nebulae which is isolated in the general field." One must, however, remain cautious about these statements in light of the surprisingly high rate of recent discoveries of new members that are low surface brightness dwarfs. These have all been discovered at distances $\ll r_0$, for obvious observational reasons, but it would be premature to exclude a significant population of low surface brightness galaxies at greater distances as well.

Adopting a half-mass radius $r_h = 0.35$ Mpc and an LG age of 14 ± 2 Gyr yields a radius $r_0 = 1.18 \pm 0.15$ Mpc for the zero-velocity surface of the LG and a total LG mass $M_{\rm LG} = (2.3 \pm 0.6) \times 10^{12}\, M_\odot$. This mass determination is valid, of course, *only if* the LG is in virial equilibrium. The fact that an equal number of LG members are blueshifted and redshifted relative to the adopted solar motion suggests that the LG may be *at least* approaching virial equilibrium. An independent "projected" mass estimate for the Andromeda subgroup, combined with mass information for the Galaxy subgroup published by Zaritsky (1999), yields nearly the same total mass for the LG, independent of any assumption about the virial nature of the LG. With this mass, the visual mass-to-light ratio (in solar units) for the LG is 44 ± 12.

Mulchaey & Zabludoff (1998) find that the velocity dispersion of clusters of galaxies and their X-ray luminosities and temperatures are related by the relations

$$\log L_{\rm X} = 31.6 \pm 1.1 + \log h^{-2} + (4.3 \pm 0.4) \log \sigma_r\,, \quad (11)$$

$$\log L_{\rm X} = 42.44 \pm 0.11 + \log h^{-2} + (2.79 \pm 0.14) \log T\,, \quad (12)$$

where the dimensionless Hubble ratio h is given by $H_0 = 100\, h$ km s^{-1} Mpc^{-1}. Extrapolating these relations to small values of σ_r, and adopting $h = 0.65$ and $\sigma_r = 61 \pm 8$ km s^{-1}, one obtains $T \approx 74$ eV and $L_{\rm X} \approx 4.5 \times 10^{39}$ ergs s^{-1} for the intracluster gas in the LG. These numbers suggest that it would be difficult, with current X-ray instrumentation and because of the strong absorption by our galaxy below 0.5 keV, to detect X-ray emission from any small group like the LG.

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