The Solar Motion Relative to the Local Group

Stéphane Courteau and Sidney van den Bergh
National Research Council, Herzberg Institute of Astrophysics
Dominion Astrophysical Observatory
5071 W. Saanich Rd, Victoria, BC V8X 4M6 Canada

ABSTRACT

New data on the membership of the Local Group, in conjunction with new and improved radial velocity data, are used to refine the derivation of the motion of the Sun relative to the Local Group (hereafter LG). The Sun is found to be moving with a velocity of $V = 306 \pm 18 \text{ km s}^{-1}$ towards an apex at $\ell = 99^\circ \pm 5^\circ$ and $b = -4^\circ \pm 4^\circ$. This 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 $61 \pm 8 \text{ km s}^{-1}$. We use various mass estimators to compute the mass of the Local Group and the Andromeda subgroup. We find $M_{\text{LG}} = (2.3 \pm 0.6) \times 10^{12} M_\odot$, from which $M/L_V = 44 \pm 12$ (in solar units). For an assumed LG age of 14 \pm 2 Gyr, the radius of an idealized LG zero-velocity surface is $r_\circ = 1.18 \pm 0.15 \text{ Mpc}$. The Local Group is found to have 35 likely members. Only three of those have (uncertain) distances $\gtrsim 1.0 \text{ Mpc}$ from the LG barycenter. Barring new discoveries of low surface brightness dwarfs, this suggests that the Local Group is more compact, and isolated from its surroundings, than previously believed.

Subject headings: galaxies: spiral — galaxies: Local Group — galaxies: kinematics and dynamics — galaxies: clusters.

1. Introduction

The motion of the Sun relative to the other members of the Local Group has been studied for many decades, with investigations by Humason, Mayall & Sandage (1956), Yahil, Tammann & Sandage (1977; hereafter YTS77), Sandage (1987), 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 Local Group in the context of 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 cosmic microwave background can be decomposed into into
a sum of local and external components:\(^1\):

\[ V_{\text{Sun} \rightarrow \text{CMB}} = V_{\text{Sun} \rightarrow \text{LSR}} + V_{\text{LSR} \rightarrow \text{GSR}} + V_{\text{GSR} \rightarrow \text{LG}} + V_{\text{LG} \rightarrow \text{CMB}}. \]  

\(^1\)Our notation is analogous to that of RG98

\( V_{\text{Sun} \rightarrow \text{LSR}} \) is the motion of the Sun relative to the nearby stars which define a Local Standard
of Rest, and the motion \( V_{\text{LSR} \rightarrow \text{GSR}} \) is the circular rotation of the LSR about the Galactic center
that is directed towards \( \ell = 90^\circ \) and \( b = 0^\circ \). Externally, \( V_{\text{GSR} \rightarrow \text{LG}} \) is the motion of the Galactic
center (or Galactic Standard of Rest) relative to the LG centroid, which is caused by non-linear
dynamics within the Local Group (mostly infall of the Galaxy toward M31). Finally, \( V_{\text{LG} \rightarrow \text{CMB}} \)
is the peculiar velocity of the Local Group in the CMB rest frame, induced by gravitational
perturbations in the Universe.

Recent discoveries of new candidate members of the Local Group, and deletion of former
candidates, have allowed us to revise the solution for the solar motion relative to the Local Group,
\( V_{\text{Sun} \rightarrow \text{LG}} \), assess Group membership, and compute a new value for the mass of the Local Group.
Three criteria are usually invoked to assess the probability that a galaxy is associated with the
Local Group: (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) it
should lie close to the ridge-line solution between radial velocity and the cosine of the angle from
the solar apex relative to well-established Local Group members, and (3), it should not appear to
be associated with any more distant group of galaxies that is centered well beyond the limits of
the Local Group. We examine these criteria below.

This paper is organized as follows. First, we compute a new solution for the motion of the
Sun relative to LG members in §3. We then estimate the radius of the zero-velocity surface in §4,
and assess Local Group 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 Local Group also include van den Bergh (1994a,b),
Grebel (1997), and Mateo (1998). The reader is referred to van den Bergh (2000; hereafter
vdB2000) for a comprehensive review on the nature of, and membership in, the Local Group.
2. The Data

A listing of information on the 32 probable (+3 possible) members of the Local Group, 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 Local Group member. Equatorial (J2000) and Galactic coordinates are listed in columns (4-7). Various photometric parameters (visual color excess, absolute visual magnitude, and distance modulus) taken from vdB2000 are listed in columns (8-10). Column (11) gives the heliocentric radial velocity of each galaxy in km s\(^{-1}\), and column (12) lists the cosine of the angle between each galaxy and the solar motion apex in the rest frame of the Local Group. Columns (13-14) give the distance of a galaxy from the Sun and from the LG barycenter in Mpc. Finally, column (15) gives the main reference to each of the radial velocities quoted in column (11). The Local Group suspects at large distances, marked with an asterisk in Table 1, are Aquarius (=DDO 210) with a distance from the LG center of 1.02 ± 0.05 Mpc (Lee 1999), Tucana at ≃ 1.10 ± 0.06 Mpc (vdB2000), and SagDIG with a poorly determined LG distance of 1.20 ≲ D ≲ 1.58 (Cook 1987). Uncertain entries in Table 1 are followed by a colon.

The positions of Local Group members in cartesian Galactocentric coordinates are shown in Fig. 1. The velocity components, X, Y, Z, of an object point toward the Galactic center (\(\ell = 0^\circ, b = 0^\circ\)), the direction of Galactic rotation (\(\ell = 90^\circ, b = 0^\circ\)), and the North Galactic Pole (\(b = 90^\circ\)).

We have calculated distances of individual galaxies, relative to the Local Group 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 more massive than the Milky Way (Mateo 1998, Zaritsky 1999, and references therein). Lacking more detailed information about the mass constituents of the Local Group, 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 Local Group barycenter is located at 0.6 times the distance to M31 at 454 kpc toward \(\ell = 121^\circ.7\) and \(b = -21^\circ.3\). This corresponds, in Galactic cartesian coordinates, 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 Figs. 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 Local Group may be smaller, and more isolated from the field, than has generally been assumed previously (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 Local Group members (Table 1), we compute a new solution for the bulk motion of the Sun relative to the Local Group centroid. The computation of a bulk flow, \( \mathbf{v}^B \), is independent of estimated distances to any of the galaxies, or the exact shape of their orbits, provided the spatial and velocity distributions are independent (e.g., YTS77, RG98). If the 3-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 \( \mathbf{v}^B \) and a 3-dimensional random isotropic Maxwellian distribution with a velocity dispersion \( \sigma_v \). The bulk flow statistics reduces to the maximisation of the likelihood function,

\[
\mathcal{L} = -\ln \sigma_v - \frac{1}{N} \sum_{k=1}^{N} \frac{(v_k^r - v_x^B \hat{r}_x^k - v_y^B \hat{r}_y^k - v_z^B \hat{r}_z^k)^2}{2\sigma_v^2},
\]

where \( v_k^r \) is the observed radial velocity of galaxy \( k \), and the components \( \{\hat{r}_j^k\}_{j=1,3} \) are the direction cosines of that galaxy. The inferred solar apex corresponds to the direction which minimizes the scatter in the distribution of radial velocities versus \( \cos \theta \), where \( \theta \) is the angle between the solar apex and the unit vector towards 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 insignificant compared with the residual velocity dispersion. They are therefore neglected. Here we adopt the values quoted by the main source in Col. (15) of Table 1. Standard deviations for the amplitude and direction of the solar motion, and for the residual velocity dispersion of the Local Group, are estimated by bootstrap resampling of the input data. The errors quoted correspond to the 1\( \sigma \) 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 \( V_\odot = 306 \pm 18 \text{ km s}^{-1} \) towards an apex at \( \ell = 99^\circ \pm 5^\circ \) and \( b = -3^\circ \pm 4^\circ \). The residual radial velocity dispersion in the Local Group is \( \sigma_v = 61 \pm 8 \text{ km s}^{-1} \). Assuming the velocity distribution of Local Group galaxies to be isotropic, the three-dimensional velocity dispersion in the Local Group is \( \simeq 106 \text{ km s}^{-1} \).

A comparison with other published solutions for the motion of the Sun relative to the Local Group 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 \( \pm 2 \text{ km s}^{-1} \). The good agreement among most published solutions is not fortuitous. Local Group dynamics are heavily dominated by systems that were already included in the sample of Mayall (1946; the earliest reference cited here). 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 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 due to 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 (7 galaxies).

For each subgroup, RG98 estimate a bulk flow using Eq. (2). They find, in Galactocentric coordinates: \(V_{\text{Galsub} \rightarrow \text{Sun}} = (94 \pm 64, -354 \pm 42, 37 \pm 33)\) km s\(^{-1}\) or \(|V_{\text{Galsub} \rightarrow \text{Sun}}| = 368 \pm 28\) km s\(^{-1}\) toward \((\ell = 285^\circ \pm 11^\circ, b = +6^\circ \pm 5^\circ)\), and \(V_{\text{Andsub} \rightarrow \text{Sun}} = (-127 \pm 541, -143 \pm 267, 301 \pm 254)\) km s\(^{-1}\) or \(|V_{\text{Andsub} \rightarrow \text{Sun}}| = 357 \pm 218\) km s\(^{-1}\) toward \((\ell = 228^\circ \pm 180^\circ, b = +58^\circ \pm 65^\circ)\). The error bars for the bulk flow estimate of the Andromeda subgroup are large, due to 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., \(V_{\text{LG} \rightarrow \text{Sun}} = (V_{\text{Galsub} \rightarrow \text{Sun}} + V_{\text{Andsub} \rightarrow \text{Sun}})/2\), which gives \(V_{\text{LG} \rightarrow \text{Sun}} = (-17 \pm 303, -249 \pm 155, 169 \pm 144)\) or \(|V_{\text{LG} \rightarrow \text{Sun}}| = 301\) km s\(^{-1}\) toward \((\ell = 266, b = +34)\). 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

\(^2\)RG98’s “Milky Way” subgroup does not include the newly discovered Sagittarius dwarf spheroidal.
flow statistics from Eq. (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 3-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 3D structure for the Local Group may be biased if the Andromeda subgroup bulk flow
$V_{Andsub\rightarrow Sun}$ differs significantly from that of the Galaxy subgroup $V_{Galsub\rightarrow Sun}$. This suggestion
is supported by RG98’s analysis and corroborated by our own reexamination of this issue. Our
analysis, based on Eq. (2), also suggests that the Andromeda subgroup would partake of a
different, stronger, bulk motion than the Galaxy subgroup. But it would be premature to make
any claims based on these results, given the large errors in the apex parameters of the Andromeda
subgroup. In any case, the poor number statistics do not allow a rejection, or confirmation, of
this hypothesis. All solutions, which account for subgrouping or a uniform structure of the Local
Group, agree to within their 1σ confidence interval.

### 3.1. A summary of corrections to radial velocities

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

$$V_{corr} = V_{hel} + V_a (\cos b \cos b_a \cos (\ell - \ell_a) + \sin b \sin b_a),$$

where $\ell$, and $b$ are the Galactic coordinates to the observed galaxy. The peculiar motion of the
Sun relative to the Local Standard of Rest (LSR) is 16.5 km s$^{-1}$ towards $\ell = 53^\circ$ and $b = +25^\circ$
(Delhaye 1965; see also Crampton 1968), or $X= +9$, $Y= +12$, and $Z= +7$ km s$^{-1}$. Therefore,

$$V_{LSR} = V_{hel} + 9 \cos \ell \cos b + 12 \sin \ell \cos b + 7 \sin b$$

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

$$V_{GSR} = V_{hel} + 9 \cos \ell \cos b + 232 \sin \ell \cos b + 7 \sin b.$$
\[ V_{\text{LG}}(\text{this paper}) = V_{\text{hel}} - 79 \cos \ell \cos b + 296 \sin \ell \cos b - 36 \sin b, \]  
\tag{6}

under the assumption that the velocity distribution function in the Local Group can be described as bulk flow plus a random isotropic Maxwellian component. Applying the same premises, but to the two main LG substructures instead of the LG as a whole as we did, RG98 find (also Table 2),

\[ V_{\text{LG}}(\text{RG98}) = V_{\text{hel}} - 18 \cos \ell \cos b + 252 \sin \ell \cos b - 171 \sin b. \]  
\tag{7}

The RC3 does not include any corrections for galaxy motions in the frame of the Local Group, on account of their ill-defined nature. This was perhaps a wise decision. The RC2 (de Vaucouleurs \textit{et al.} 1976) reports the “old” solar apex solution \((300 \sin \ell \cos b)\), but modern solutions (Table 2) show deviations from the RC2 formulation as large as \(\pm 87\, \text{km s}^{-1}\), as already noted by YTS77. Perhaps even more important are the deviations that exist between our solution and RG98. The maximum deviations (Eqs. 6-8) are \(\pm 154\, \text{km s}^{-1}\) toward \((\ell = 145^\circ, b = 60^\circ)\) and \((\ell = 325^\circ, b = -60^\circ)\). These are shown in Figure 4; negative and positive residuals are 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 \textit{et al.} 1993). Under the assumption that the CMB dipole is kinematic in origin, and not due to any external force field, this operation carries little uncertainty. On the other hand, the transformation to the Local Group 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 (\textit{e.g.}, Table 2). However, this result is either due to the regular nature of the LG or to the fact that we are making similar erroneous assumptions. The kinematical method described above can lead to biased results if the phase-space galaxy distribution is not homogenous. Use of a dynamical 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 Local Group, which is lacking at present. Clearly, it is the prerogative of the astronomer to adopt (and justify) whatever cosmological rest frame he/she prefers.

Given that the mean motion of the Local Group is consistent with the combined motion of its two main substructures, we will adopt the “standard” solution [Eq.\,(6)] as the best description for solar motion relative to the Local Group. However, one should keep in mind the main caveats/assumptions for this solution, as we reiterate in \S 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 Local Group can be computed from its velocity dispersion as (Spitzer 1969; see also Binney & Tremaine 1987, eq. 4-80b):

$$M_{LG} \simeq \frac{7.5}{G} \langle \sigma^2_r \rangle r_h = 1.74 \times 10^6 \langle \sigma^2_r \rangle r_h M_\odot,$$

(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 $r_h \lesssim 450$ kpc. This number-weighted figure is clearly an upper limit to the actual mass-weighted estimate. If M31 accounts for $\sim 60\%$ of the mass in the Local Group, 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 $M_{LG} = (2.3 \pm 0.6) \times 10^{12} M_\odot$.

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 et al. (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:

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

(9)

where $R$ is the projected separation from M31 (assuming $D_{M31} = 760$ kpc), and $V_{zi}^2$ is the radial velocity in the frame of M31. Table 3 gives the relevant parameters for all 7 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 non-isotropic. However, taken at face value, this result suggests that most of the dark and luminous mass in the Local Group is locked into the Andromeda and Galactic subgroups, unless the intra-cluster dark matter is distributed in a highly flattened shape. The timing argument by Kahn and Woltjer (1959), which is based on the motion of M31 towards the Galaxy yields a minimum Local Group mass of $\sim 18 \times 10^{11} M_\odot$. Sandage (1986), using a similar argument for the deceleration of nearby galaxies caused by the Local Group, finds a maximum mass for the Local Group 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 Local Group. The formula he used for the virial mass differs by a factor 7.5 from ours (Eq. 8),
Table 3

The Andromeda Sub-Group

<table>
<thead>
<tr>
<th>Name</th>
<th>$R^{a}$</th>
<th>$v_{hel}$</th>
<th>$v_{cor}^{b}$</th>
<th>$q^{c}/10^{11}M_{\odot}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>M 32</td>
<td>5.3</td>
<td>-205</td>
<td>95</td>
<td>0.11</td>
</tr>
<tr>
<td>NGC 205</td>
<td>8.0</td>
<td>-244</td>
<td>58</td>
<td>0.06</td>
</tr>
<tr>
<td>NGC 185</td>
<td>93.9</td>
<td>-202</td>
<td>107</td>
<td>2.49</td>
</tr>
<tr>
<td>NGC 147</td>
<td>98.3</td>
<td>-193</td>
<td>118</td>
<td>3.18</td>
</tr>
<tr>
<td>M 33</td>
<td>197.3</td>
<td>-181</td>
<td>72</td>
<td>2.37</td>
</tr>
<tr>
<td>IC 10</td>
<td>242.9</td>
<td>-344</td>
<td>-29</td>
<td>0.48</td>
</tr>
<tr>
<td>Pisces</td>
<td>263.0</td>
<td>-286</td>
<td>-38</td>
<td>0.90</td>
</tr>
</tbody>
</table>

Table 3: (a) The projected separations in kpc are based on a distance to M31 of 760 kpc. Compare with Bahcall & Tremaine 1981, Table 4.; (b) The velocities $v_{cor}$ 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. $v_{cor} = V_{GSR} + 124 \cos b \cos(-21.3) \cos(\ell - 121.7) + \sin b \sin(-21.3)$; (c) The projected mass $q = v^{2}z/R/G M_{\odot}$ 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 $\sim 2$ (if $r_{h} \simeq 0.4r_{g}$). This explains the discrepancy “by a factor of 7” (with Kahn-Woltjer) discussed by Sandage. Moreover, his result that $M_{LG} = 4 \times 10^{11} M_{\odot}$ based on a velocity perturbation analysis of the Local Group, assumes a formation age of 18.1 Gyr ($H_{0}=55$ km s$^{-1}$ Mpc$^{-1}$ for an $\Omega = 0$ Universe), and that $M_{M31} = 2 M_{Gal}$. Adoption of revised figures, $H_{0}=65$ km s$^{-1}$ Mpc$^{-1}$ and $M_{M31} = 1.5 M_{Gal}$, yield a model-data comparison that agrees perfectly well with $M_{LG} = (2.3 \pm 0.6) \times 10^{12} M_{\odot}$ (see Sandage 1986, fig. 11). Thus, both calculations in Sandage (1986) are consistent with a higher value for $M_{LG}$, equal to the one we measure.

From the absolute magnitudes of LG galaxies listed in Table 1, we compute the total luminosity of the Local Group to be $L_{V} = 5.2 \times 10^{10} L_{\odot}$, corresponding to $M_{V}(LG) = -22.0$. Combined with our estimate of the virial mass, and assuming a 10% error in $L_{V}$, we measure $M/L_{V} = 44 \pm 12$ in solar units$^{5}$. 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) contributes significantly to the error of the integrated luminosity of the Local Group.

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 Eq. (7) of Sandage (1986):

\[
 r_\circ [\text{Mpc}] = \left( \frac{8 G T^2}{\pi^2} M_{\text{LG}} \right)^{1/3} = 0.154 \left( T [\text{Gyr}] \right)^{2/3} \left( M_{\text{LG}}[10^{12} \text{M}_\odot] \right)^{1/3}. \quad (10)
\]

Assuming that the age of the Local Group is \(14 \pm 2\) Gyr, and using our estimate of the virial mass of the Local Group, we find \(r_\circ = 1.18 \pm 0.15\) Mpc. The value of \(r_\circ\) 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 Local Group: (1) the Sculptor irregular (=UKS 2323-326), (2) Maffei 1 and its companions, (3) UGC-A86 (=A0355+66), (4) NGC 1560, (5) NGC 5237, and (6) DDO 187. A particularly strong concentration of Local Group suspects, which includes (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 \(3.6 \pm 0.5\) Mpc. Cassiopeia 1, regarded as a Local Group suspect (Tikhonov 1996), also appears to be a member of the IC 342/Maffei group. Van den Bergh & Racine (1981) failed to resolve Local Group suspect LGS2 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 long-time Local Group 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 Local Group boundary. The spiral galaxy NGC 55 has recently been listed as a possible Local Group 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, Jørgen, Freeman, & Bingelli (1998) place NGC 55 on the near side of the Sculptor group. We have also excluded the galaxies NGC 3109, Antlia, Sextans A, and Sextans B from membership in the Local Group. These objects, which have measured distances of \(1.36, 1.70, 1.45\) and \(1.32\) Mpc respectively (vdB2000), are located relatively close together on the sky. Their mean distance from the barycenter of the Local
Group, which is situated \( \sim 450 \) kpc away in the direction towards M 31, is 1.7 Mpc. Furthermore these galaxies have a mean redshift of \( 114 \pm 12 \) km s\(^{-1}\) relative to the \( V_r - \cos \theta \) relation derived in §3 (see vdB2000). These data suggest that NGC 3109, Antlia, Sex A and Sex 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 N3109, Sextans A, and Sextans B were also excluded by YTS77 on the basis of their solar motion solutions. Zilstra & Minniti (1998) find that the LG candidate IC 5152 is located at \( 1.8 \pm 0.2 \) Mpc, which places it outside the LG zero-velocity surface.

Group membership can be revised by inspection of the \( V_r - \cos \theta \) diagram, which illustrates the motions of individual galaxies with respect to the ensemble of the galaxies in the Group. This is shown in Figure 4 for LG galaxies. The LG radial velocity dispersion, \( \sigma_r = 61 \pm 8 \) km s\(^{-1}\), is shown by dotted lines. Suspected outliers lying below the 1\( \sigma \) regression line are few. None of the systems presented in Fig. 4 can be excluded from membership on the basis of this test. The two blue-shifted systems (IC 1613 and Pisces), and handful of redshifted LG objects, fall within 2\( \sigma \) 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 SagDIG are so far from the barycenter of the LG that their membership in the Local Group cannot yet be regarded as firmly established, even though they lie close to the solar ridge-line in the \( V_r - \cos \theta \) diagram.

It might be argued that our value of \( \sigma_r \) is biased low because the data base may lack (unknown) nearby fast-moving galaxies. However, this effect is probably not important because no galaxy are found with large blue-shifts relative to the mean relationship between \( \cos \theta \) and apex distance.

6. Discussion and Summary

We have measured a new solution for the solar motion relative to LG galaxies which agrees very well with previous derivation 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 3-dimensional spatial and velocity distributions are independent. This would not be true if the LG potential is 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 if their combined motion matches that inferred relative to the entire Local Group. 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 \( V_{\text{Sun} \rightarrow \text{Andsub}} \)) 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 \( V_{\text{Sun-LG}} = 306 \pm 18 \, \text{km s}^{-1} \) towards an apex at \( \ell = 99^\circ \pm 5^\circ \) and \( b = -4^\circ \pm 4^\circ \). It is worth pointing out that interpretation errors for the solar motion may linger until we get a better understanding of the true orbital motions of LG members, and a better knowledge of the overall distribution of mass in the Local Group.

The observed radial velocity dispersion of the LG is \( \sigma_r = 61 \pm 8 \, \text{km s}^{-1} \). Braun & Burton (1998) measured a radial velocity dispersion \( \sigma_r = 69 \, \text{km s}^{-1} \) for the motion of intra-cluster compact HI high-velocity clouds (HVCs). Although close in dispersion to the LG value, HVCs exhibit an excess of infall velocities (blue-shifts) suggesting that many of them may presently still be falling into the Local Group, contrary to bona fide LG galaxies.

Table 1 presents an updated listing of 35 probable members of the Local Group. Half of all the members are located within 450 kpc of the barycenter of the LG, with only 3 objects, SagDIG, 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” (1936): “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 recent, surprisingly high, rate of discoveries of new members that are low surface brightness dwarfs. These have all been discovered at distances \(< r_o\), 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 \( r_h = 0.35 \, \text{Mpc} \) and a LG age of \( 14 \pm 2 \, \text{Gyr} \) yields a radius \( r_o = 1.18 \pm 0.15 \, \text{Mpc} \) for the zero-velocity surface of the Local Group, and a total LG mass \( M_{\text{LG}} = (2.3 \pm 0.6) \times 10^{12} \, M_\odot \). This mass determination is, of course, only valid if the LG is in virial equilibrium. The fact that an equal number of LG members are blue-shifted 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 published mass information for the Galaxy subgroup by Zaritsky (1999), yield 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 \( 44 \pm 12 \).

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

\[
\log L_X = 31.6 \pm 1.1 + \log h^{-2} + (4.3 \pm 0.4) \log \sigma_r, \quad (11)
\]

and

\[
\log L_X = 42.44 \pm 0.11 + \log h^{-2} + (2.79 \pm 0.14) \log T, \quad (12)
\]
where the dimensionless Hubble ratio $h$, is given by $H_0 = 100 \, h \, \text{km s}^{-1} \, \text{Mpc}^{-1}$. Extrapolating these relations to small values of $\sigma_r$, and adopting $h = 0.65$ and $\sigma_r = 61 \pm 8 \, \text{km s}^{-1}$, one obtains $T \approx 74 \, \text{eV}$ and $L_X \approx 4.5 \times 10^{39} \, \text{erg s}^{-1}$ for the intra-cluster gas in the Local Group. These numbers suggest that it would be difficult, with current X-ray instrumentation and due to the strong absorption by our galaxy below 0.5 keV, to detect X-ray emission from any small group like the LG.

**Acknowledgements**

We would like to thank Stéphane Rauzy for sharing his likelihood estimator and useful comments on the paper.
REFERENCES

Cook, K.H. 1968, Ph.D. Thesis, Univ. of Arizona
Crampton, D. 1968, PASP, 80, 475
Harris 1996 AJ, 112, 1487
Heisler, J., Tremaine, S. & Bahcall, J. N., 1985, 298, 8
Kerr, F.J. & Lynden-Bell, D., 1986, 221, 1023


Lynden-Bell, D. 1981, Observatory, 101, 111


Spitzer, L. 1969, ApJL, 158, 139


van den Bergh, S. 1971, Nature, 231, 35

van den Bergh, S. 1981, PASP, 93, 428


van den Bergh, S. 1994a, in *The Local Group*, Eds. A. Layden, R.C. Smith and J. Storm (Garching: ESO), p. 3


van den Bergh, S. 1994b, AJ, 107, 1328

This preprint was prepared with the AAS L\LaTeX macros v4.0.
Fig. 1.— Positions of Local Group members in Galactic cartesian coordinates, as viewed from two orthogonal directions. The left side shows a sphere of radius $r_o = 1.18$ Mpc (corresponding to the zero-velocity surface of the Local Group) 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 dots 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 $D_{LG} \simeq 0.85$ Mpc. The density of galaxies near $D_{LG} = 0$ 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 Local Group has $\lesssim 0.85$ Mpc. Half of the known members of the Local Group are seen to located within 450 kpc of the adopted barycenter.

Fig. 4.— Aitoff projection in Galactic coordinates showing the residuals between our solution for the solar motion relative to the Local Group (Eq. 6) and that of Rauzy & Gurzadyan (1998; 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 $\ell = 145^{\circ}, b = 60^{\circ}$, and $-154$ km s$^{-1}$ toward $\ell = 325^{\circ}, b = -60^{\circ}$. Positive and negative residuals (This paper - RG98) are shown with circles and stars, respectively.

Fig. 5.— Observed heliocentric velocities $V_r$ of Local Group members versus $\cos \theta$, where $\theta$ is the angular distance from the solar apex. Our solar motion solution of $306 \pm 18$ km s$^{-1}$ towards $\ell = 99^{\circ} \pm 5^{\circ}$ and $-3^{\circ} \pm 4^{\circ}$ is shown as the solid ridge line. Dotted lines correspond to the residual radial velocity dispersion of $\pm 61$ 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 Local Group members.

Fig. 6.— Same as Figure 5 but using the solar motion solution of Rauzy & Gurzadyan (1998) with $V_\odot = 306 \pm 18$ km s$^{-1}$ towards $\ell = 94^{\circ} \pm 48^{\circ}$ and $-34^{\circ} \pm 29^{\circ}$. For comparison, the solid ridge line and dotted dispersion lines are those computed for Figure 5. Note that the dispersion around the regression relation of Rauzy & Gurzadyan (1998; Eq. 7) is twice larger ($\sigma_r = 110.3$ km s$^{-1}$) than that for the Standard solution shown in Figure 5.