ORBITAL MASSES OF NEARBY LUMINOUS GALAXIES

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ABSTRACT

We use observational properties of galaxies accumulated in the Updated Nearby Galaxy Catalog to derive a dark matter mass of luminous galaxies via motions of their companions. The data on orbital-to-stellar mass ratio are presented for 15 luminous galaxies situated within 11 Mpc from us: the Milky Way, M31, M81, NGC 5128, IC342, NGC 253, NGC 4736, NGC 5236, NGC 6946, M101, NGC 4258, NGC 4594, NGC 3115, NGC 3627, and NGC 3368, as well as for a composite suite around other nearby galaxies of moderate and low luminosity. The typical ratio for these galaxies is $M_{\text{orb}}/M_*=31$, corresponding to the mean local density of matter $\Omega_m = 0.09$, i.e., one-third of the global cosmic density. This quantity seems to be rather an upper limit of dark matter density, since the peripheric population of the suites may suffer from the presence of fictitious unbound members. We note that the Milky Way and M31 halos have lower dimensions and lower stellar masses than those of the other 13 nearby luminous galaxies. However, the dark-to-stellar mass ratio for both the Milky Way and M31 is typical for other neighboring luminous galaxies. The distortion in the Hubble flow, observed around the Local Group and five other neighboring groups, yields their total masses within the radius of a zero velocity surface, $R_0$; these masses are slightly lower than the orbital and virial values. This difference may be due to the effect of dark energy producing a kind of “mass defect” within $R_0$.

Key words: cosmology: observations – dark matter – galaxies: groups: general

1. INTRODUCTION

In spite of the tremendous success of observational cosmology over the past quarter century, many issues regarding the nature of dark matter and its distribution in the universe relative to the visible (stellar) matter still remain unresolved. Numerous studies (Karachentsev 1996; Rood et al. 1970; Bahcall et al. 2000) have shown that in groups and clusters of galaxies, the ratio of dark (virial) mass to stellar mass systematically increases with the size and population of a given system of galaxies. In the richest clusters, such as the Coma Cluster, the $M_{\text{DM}}/M_*$ ratio can be up to two orders of magnitude. If all galaxies are parts of clusters, the dark matter associated with them would provide an average density of matter in space amounting to $\Omega_m \simeq 0.26$ (Bahcall & Gulier 2014), corresponding to the standard cosmological $\Lambda$CDM model (Spergel et al. 2007).

However, no more than 10% of all galaxies belong to rich clusters (Libeskind et al. 2013; Cautun et al. 2014). Most of them are included in groups of different multiplicity that are concentrated in the filaments and “sheets,” forming a large-scale “cosmic web” (Bond et al. 1996; Shandarin et al. 2004; Einasto et al. 2011). Looking at the data on 11,000 galaxies in the nearby universe with radial velocities $V_{LG} \leq 3500$ km s$^{-1}$, Makarov & Karachentsev (2011) have identified about 400 groups and clusters of galaxies in this volume and have determined their virial masses. The total virial mass of groups and clusters in the volume of about 50 Mpc radius led to the average density estimate of $\Omega_m(\text{local}) \simeq 0.08 \pm 0.02$, which is three times lower than the global cosmic density. This result confirmed the earlier estimates of $\Omega_m \sim (0.08-0.10)$, which were obtained for the local universe by Vennik (1984), Tully (1987), Magtesian (1988), and other authors. A threefold difference between the estimates of $\Omega_m(\text{local})$ and $\Omega_m(\text{global})$ did not cause much concern among theorists. It was considered quite obvious that dark matter is not distributed in clusters and groups with the same concentration as stellar matter (the biasing effect). Darker peripheries of the clusters probably contain a large amount of dark matter, the presence of which eliminates the paradox of “missing dark matter.”

The assumption that massive dark halos exist around clusters and groups of galaxies is not, however, confirmed by observations. Investigating the Hubble flow of galaxies around Virgo, the nearest cluster of galaxies, Karachentsev et al. (2014b) showed that the total mass of the cluster, determined from the external motions of galaxies, is in good agreement with the virial mass estimate based on the motions within the cluster. Since the total mass of the Virgo cluster was estimated on a scale of the “zero velocity sphere” radius, $R_0$, which is $\sim 3.7$ times larger than the virial radius $R_v$, this result gives evidence against the localization of a significant amount of dark matter in the layer between $R_v$ and $R_0$. A similar situation occurs around the Local Group of galaxies (Karachentsev et al. 2009). Consequently, we should be on the lookout for other ideas and observational data to resolve the paradox of missing dark matter.

The recently published Updated Nearby Galaxy Catalog (UNGC; Karachentsev et al. 2013) contains a summary of data on radial velocities, distances, and other observable parameters of about 800 galaxies located within a 11 Mpc radius around us. More than 300 galaxies of this sample have accurate distance measurements with a better than 10% accuracy obtained by the tip of the red giant branch from observations with the Hubble Space Telescope. Due to the proximity of the UNGC objects, the kinematic data density in the catalog proves to be six times higher than in the sample of the nearby $(D \leq 50$ Mpc) universe (Makarov & Karachentsev 2011, hereafter MK11). This circumstance and the presence of individual distance measurements in many UNGC galaxies allow us to investigate the structure of nearby groups and their vicinities with unprecedented detail. Determining the masses of the most...
nearby galaxies from the motions of their companions is the main subject of this paper.

2. PROJECTED AND ORBITAL MASS ESTIMATES

To determine the mass of a system of \( N \) point-like bodies, one usually uses the virial theorem in the form of

\[
M_v = \frac{(3\pi/2) \times G^{-1} \times S_v^2 \times R_h^{-1}},
\]

where \( G \) is the gravitational constant, \( S_v^2 \) is the velocity dispersion on the line of sight, \( R_h \) is the average harmonic separation between the group members in the projection on the sky, and \((3\pi/2)\) is the average projection factor at an arbitrary group orientation with respect to the line of sight (Bahcall & Tremaine 1981). However, this estimator is statistically offset and inefficient. Therefore, Heisler et al. (1985) proposed estimating the mass of a group in a more robust way:

\[
M_p = \frac{(32/\pi) \times N \times (N - 3/2)^{-1} \times G^{-1} \times (\Delta V^2 \times R_p)},
\]

where \( M_p \) is the so-called “projected” mass, \( N \) is the number of objects, and \((\Delta V^2 \times R_p)\) is the average product of the squared radial velocity of the component relative to the group center, and its projection separation from the center. Both these mass estimators presume spherical symmetry of the groups as well as isotropic velocity distribution. As shown by Wojtak (2013), however, many groups are highly aspherical, with shapes approximated by nearly prolate ellipsoids. According to Wojtak (2013), the mean spatial axial ratio of these groups is \( \sim 0.66 \) and the mean axial ratio of the velocity ellipsoids is \( \sim 0.78 \). Furthermore, simulated dark matter halos tend to be aligned with the cosmic web in the way that the semi-major axis is aligned with the local filaments and the semi-minor axis is pointing to neighboring voids (Libeskind et al. 2013). Being mostly located in the Local Sheet, the nearby groups may be preferentially observed along their major or median axes, which would have an effect on the mass estimates.

If the group is dominated by a massive galaxy surrounded by a set of test particles with random orientation of their orbits, one can use the “orbital” mass estimate (Karachentsev 2005):

\[
M_{\text{orb}} = \frac{(32/3\pi)(1 - 2\epsilon^2/3)^{-1} \times G^{-1} \times (\Delta V_{12}^2 \times R_{p12})},
\]

where \( \Delta V_{12} \) and \( R_{p12} \) are the velocity difference and the projected separation of companions relative to the main galaxy, and \( \epsilon \) is the prevailing orbit eccentricity. Assuming the typical eccentricity value of \( \epsilon^2 \approx 1/2 \) (Barber et al. 2014), we get

\[
M_{\text{orb}} = \frac{(16/\pi) \times G^{-1} \times (\Delta V_{12}^2 \times R_{p12})}.
\]

For completeness, we also mention another approach to mass estimation proposed by Beloborodov & Levin (2004). Based on the natural assumption that companions of the main galaxy are observed at random orbital phase moments, they offered the so-called “orbital roulette estimator,”

\[
M_{\text{Or}} = 6 \times (2 - \langle \epsilon^2 \rangle)^{-1} \times G^{-1} \times (\Delta V_{12}^2 \times R_{p12}),
\]

which uses the same observables, but yields at \( \langle \epsilon^2 \rangle = 1/2 \) a mass estimate 21% smaller than Equation (4). Note that at \( N = 2 \), the projected mass estimate (2) coincides with the orbital estimate (4). We will use the orbital mass estimator later.

3. NEIGHBORING GIANTS AND THEIR SUITES

Possessing the data on the distances and luminosities of 869 galaxies in the Local Volume, Karachentsev et al. (2013) have determined the tidal index of each galaxy

\[
\Theta_1 = \max \left[ \log \left( \frac{M^*}{D_{n}} \right) \right] + C, \quad n = 1, 2, \ldots N,
\]

where \( M^* \) is the stellar mass of the neighboring galaxy, and \( D_n \) is its spatial separation from the considered galaxy. The stellar mass of the galaxy was assumed to be equal to its \( K \)-band luminosity at \( M^*/L_K = M_0/L_0 \) (Bell et al. 2003). Ranking the surrounding galaxies by the magnitude of their tidal force, \( F_n \sim M^*/D_n^2 \), allowed us to find the most influential neighbor, which we called the Main Disturber (MD). Here the ratio of the total mass of the galaxy to its stellar mass was considered to be constant regardless of the luminosity and morphology of galaxies. The constant \( C = -10.96 \) in Equation (6) was chosen so that the galaxy with \( \Theta_1 = 0 \) was located at the “zero velocity sphere” relative to its MD. In other words, the galaxy with \( \Theta_1 > 0 \) was regarded as causally (gravitationally) related to its MD as the crossing time was shorter than the age of the universe, \( t_0 = 13.7 \) Gyr. Consequently, the causally unrelated galaxies with \( \Theta_1 < 0 \) were referred to as the population of the “general field.”

Obviously, the galaxies that have a common MD can be combined into a certain association, or an MD “suite.” Among these lists, an aggregate of suite members with positive \( \Theta_1 \) values is quite consistent with the notion of a physically bound group of galaxies. Karachentsev et al. (2014a) have analyzed different properties of galaxies in the suites, as well as properties of their main galaxies. As expected, the most massive MDs possess the most populous suites. The total number of companions around the 15 most massive galaxies makes up about half of the total population of the Local Volume.

The full list of suites, ranked by the number of suite members from \( n = 53 \) to \( n = 1 \) is presented in Table 1 of Karachentsev et al. (2014a). Table 1 presents the summary of the 15 richest suites in the Local Volume, in which at least 6 galaxies have measured radial velocities. We did not include in Table 1 members of suites for which radial velocities remain unmeasured. These cases consist of about one-third of the total amount of suite members.

The heading line of each suite presents the name of the MD, its distance in megaparsecs, its stellar mass, and the value of the orbital mass with the standard error. The suites (groups) are arranged in the descending order of \( \Theta_1 \), which we called the Main Disturber (MD). Along with the name of the group, the values of the tidal index, the mass of the galaxy, and its distance in kiloparsecs, are given. Additionally, the number of companions around the main galaxy is presented in three panels of Figure 1. The upper panel shows the \((M^*/V_\text{T})\) diagram for 31 companions of the Milky Way (MW, squares) and 39 members of the M31 (Andromeda) suite (diamonds). The companions of massive galaxies with a tidal index of \( \Theta \geq 0 \), which is considered

\footnote{An updated machine-readable version of this table is available at http://www.sao.ru/lv/lvgdb/tables.php.}
### Table 1

**M81**

$D = 3.63 \text{ Mpc}, M_* = 8.51 \times 10^{10} M_\odot, M_{\text{orb}} = (4.89 \pm 1.42) \times 10^{12} M_\odot$

| Name                  | $\Theta_1$ | $R_p$ | $|dV|$ |
|-----------------------|------------|-------|------|
| 1 HolmIX              | 5.1        | 11    | 88   |
| 2 ClumpI              | 4.2        | 24    | 129  |
| 3 KDG061              | 4.0        | 31    | 256  |
| 4 [CKT2009]d9059+68   | 4.0        | 35    | 150  |
| 5 ClumpIII            | 3.9        | 39    | 85   |
| 6 NGC 2976            | 2.9        | 88    | 38   |
| 7 MESSIER082          | 2.8        | 39    | 224  |
| 8 KDG064              | 2.7        | 103   | 17   |
| 9 IKN                 | 2.5        | 84    | 105  |
| 10 HIIASS J1021+6842  | 2.3        | 147   | 83   |
| 11 F8D1               | 2.2        | 119   | 96   |
| 12 KDG063             | 2.0        | 169   | 104  |
| 13 DDO078             | 1.9        | 201   | 87   |
| 14 HolmI              | 1.7        | 157   | 187  |
| 15 KDG073             | 1.4        | 323   | 159  |
| 16 UGCS05497          | 1.4        | 333   | 163  |
| 17 HS117              | 1.2        | 191   | 12   |
| 18 BK3N               | 1.2        | 12    | 3    |
| 19 DDO082             | 1.1        | 215   | 103  |
| 20 [CKT2009]d9058+66  | 1.0        | 142   | 117  |
| 21 IC2574             | 1.0        | 193   | 79   |
| 22 KDG052             | 0.8        | 511   | 167  |
| 23 DDO053             | 0.8        | 525   | 46   |
| 24 HolmII             | 0.7        | 536   | 207  |
| 25 UGCS04483          | 0.6        | 440   | 200  |
| 26 KKH37              | 0.0        | 1030  | 110  |

**M31**

$D = 0.77 \text{ Mpc}, M_* = 5.37 \times 10^{10} M_\odot, M_{\text{orb}} = (1.76 \pm 0.33) \times 10^{12} M_\odot$

| Name                  | $\Theta_1$ | $R_p$ | $|dV|$ |
|-----------------------|------------|-------|------|
| 34 And XXVIII         | 1.1        | 407   | 3    |
| 35 Pegasus            | 0.9        | 463   | 89   |
| 36 IC1613             | 0.7        | 634   | 60   |
| 37 And XVIII          | 0.4        | 112   | 15   |
| 38 Cetus              | 0.3        | 1002  | 55   |
| 39 WLM                | 0.0        | 1209  | 13   |

**MW**

$D = 0.01 \text{ Mpc}, M_* = 5.00 \times 10^{10} M_\odot, M_{\text{orb}} = (1.35 \pm 0.47) \times 10^{12} M_\odot$

| Name                  | $\Theta_1$ | $R_p$ | $|dV|$ |
|-----------------------|------------|-------|------|
| 1 Sag dSph            | 5.3        | 5     | 169  |
| 2 Segue I             | 4.3        | 17    | 111  |
| 3 UMa II              | 3.9        | 21    | 33   |
| 4 BootesII            | 3.8        | 37    | 116  |
| 5 Segue 2             | 3.8        | 22    | 43   |
| 6 Willman1            | 3.7        | 34    | 36   |
| 7 Comal               | 3.7        | 40    | 82   |
| 8 BootesIII           | 3.6        | 49    | 241  |
| 9 LMC                 | 3.5        | 49    | 84   |
| 10 Uimin              | 3.2        | 59    | 93   |
| 11 BootesI            | 3.2        | 66    | 106  |
| 12 Draco              | 2.9        | 80    | 101  |
| 13 Sculptor           | 2.7        | 90    | 72   |
| 14 SexDSph            | 2.7        | 85    | 75   |
| 15 Carina             | 2.6        | 99    | 13   |
| 16 UMa I              | 2.5        | 84    | 7    |
| 17 Hercules           | 2.1        | 107   | 145  |
| 18 Fornax             | 2.1        | 137   | 60   |
| 19 LeoIV              | 2.0        | 160   | 10   |
| 20 CVnII              | 2.0        | 160   | 96   |
| 21 LeoV               | 1.8        | 180   | 58   |
| 22 LeoII              | 1.6        | 201   | 32   |
| 23 CVnI               | 1.5        | 220   | 78   |
| 24 Leol               | 1.4        | 223   | 175  |
| 25 LeoT               | 0.7        | 338   | 57   |
| 26 Phoenix            | 0.7        | 440   | 142  |
| 27 NGC 6822           | 0.5        | 257   | 43   |

**NGC 5128**

$D = 3.75 \text{ Mpc}, M_* = 8.13 \times 10^{10} M_\odot, M_{\text{orb}} = (6.71 \pm 2.09) \times 10^{12} M_\odot$

| Name                  | $\Theta_1$ | $R_p$ | $|dV|$ |
|-----------------------|------------|-------|------|
| 1 ESO324-024          | 2.9        | 104   | 38   |
| 2 ESO269-066          | 2.0        | 190   | 218  |
| 3 NGC 5011C           | 2.0        | 148   | 84   |
| 4 ESO270-017          | 1.8        | 198   | 273  |
| 5 K196                | 1.6        | 141   | 180  |
| 6 K211                | 1.6        | 242   | 50   |
| 7 NGC 5237            | 1.2        | 146   | 188  |
| 8 ESO325-011          | 1.1        | 248   | 1    |
| 9 NGC 5206            | 1.0        | 350   | 24   |
| 10 K221               | 1.0        | 376   | 42   |
| 11 NGC 4945           | 0.9        | 482   | 11   |
| 12 NGC 5102           | 0.8        | 422   | 83   |
| 13 ESO383-087         | 0.6        | 549   | 202  |
| 14 PGC051639          | 0.3        | 768   | 133  |
| 15 NGC 5253           | 0.3        | 779   | 117  |

**NGC 4594**

$D = 9.30 \text{ Mpc}, M_* = 19.95 \times 10^{10} M_\odot, M_{\text{orb}} = (28.47 \pm 17.80) \times 10^{12} M_\odot$

| Name                  | $\Theta_1$ | $R_p$ | $|dV|$ |
|-----------------------|------------|-------|------|
| 1 SUCD1               | 6.5        | 8     | 215  |
| 2 KKS30               | 1.2        | 458   | 23   |
| Name               | $d$ (Mpc) | $M_*$ ($M_\odot$) | $R_{p}$ | $M_{\text{orb}}$ ($M_\odot$) | $dV$ |
|-------------------|-----------|-------------------|--------|------------------|------|
| NGC 4594          | 9.30      | 19.95×10^10       | 36     | (28.47±17.80)×10^{12} $M_\odot$ |      |
| Name              | $\Theta_1$ | $R_p$ | $dV$ |
| 3 LV J1235-1104   | 0.8       | 194              | 109    |                      |      |
| 4 MCG-02-33-075   | 0.4       | 757              | 279    |                      |      |
| 5 DDO148          | 0.2       | 1097             | 276    |                      |      |
| 6 NGC 4597        | 0.0       | 949              | 18     |                      |      |
| NGC 3368          | 10.42     | 6.76×10^{10}      | 62     | (17.00±4.30)×10^{12} $M_\odot$ |      |
| Name              | $\Theta_1$ | $R_p$ | $dV$ |
| 1 LeG13           | 3.1       | 82               | 22     |                      |      |
| 2 LeG17           | 2.9       | 92               | 140    |                      |      |
| 3 FS04            | 1.8       | 231              | 119    |                      |      |
| 4 UGC05812        | 1.5       | 285              | 117    |                      |      |
| 5 AGC202456       | 1.5       | 285              | 71     |                      |      |
| 6 NGC 3412        | 1.3       | 343              | 38     |                      |      |
| 7 LeG05           | 1.3       | 346              | 111    |                      |      |
| 8 AGC205268       | 1.1       | 390              | 261    |                      |      |
| 9 NGC 3351        | 1.1       | 126              | 117    |                      |      |
| 10 AGC205445      | 1.1       | 398              | 250    |                      |      |
| 11 LSBC D64-12    | 1.0       | 419              | 41     |                      |      |
| 12 LSBC D64-13    | 1.0       | 423              | 100    |                      |      |
| 13 AGC200499      | 0.9       | 466              | 273    |                      |      |
| 14 LeG06          | 0.8       | 486              | 123    |                      |      |
| 15 NGC 3299       | 0.8       | 488              | 287    |                      |      |
| 16 UGC06014       | 0.8       | 491              | 232    |                      |      |
| 17 AGC202248      | 0.7       | 531              | 280    |                      |      |
| 18 AGC205156      | 0.3       | 716              | 22     |                      |      |
| 19 AGC205165      | 0.2       | 771              | 154    |                      |      |
| 20 LeG03          | 0.2       | 782              | 247    |                      |      |
| NGC 4258          | 7.83      | 8.71×10^{10}      | 58     | (3.16±1.01)×10^{12} $M_\odot$ |      |
| Name              | $\Theta_1$ | $R_p$ | $dV$ |
| 1 NGC 4242        | 1.8       | 233              | 62     |                      |      |
| 2 NGC 4288        | 1.7       | 144              | 82     |                      |      |
| 3 NGC 4248        | 1.1       | 30               | 38     |                      |      |
| 4 LV J1203+4739   | 0.9       | 372              | 41     |                      |      |
| 5 KDG101          | 0.7       | 30               | 316    |                      |      |
| 6 NGC 4144        | 0.6       | 239              | 189    |                      |      |
| 7 KK133           | 0.5       | 536              | 95     |                      |      |
| 8 UGC07639        | 0.4       | 255              | 56     |                      |      |
| 9 DDO120          | 0.3       | 211              | 10     |                      |      |
| 10 MAPP1249+44    | 0.2       | 834              | 66     |                      |      |
| 11 UGC07827       | 0.1       | 597              | 103    |                      |      |
| NGC 4736          | 4.66      | 4.07×10^{10}      | 112    | (2.67±0.90)×10^{12} $M_\odot$ |      |
| Name              | $\Theta_1$ | $R_p$ | $dV$ |
| 1 IC3687          | 1.4       | 252              | 25     |                      |      |
| 2 IC4182          | 0.9       | 370              | 5      |                      |      |
| 3 KK160           | 0.8       | 232              | 6      |                      |      |
| 4 UGC08215        | 0.5       | 530              | 48     |                      |      |
| 5 DDO120          | 0.4       | 497              | 122    |                      |      |
| 6 NGC 4499        | 0.3       | 418              | 103    |                      |      |
| 7 NGC 4244        | 0.3       | 592              | 93     |                      |      |
| 8 DDO168          | 0.3       | 525              | 82     |                      |      |
| 9 CGCG 189-050    | 0.2       | 485              | 16     |                      |      |
| 10 DDO169         | 0.2       | 634              | 4      |                      |      |
| 11 DDO167         | 0.1       | 539              | 122    |                      |      |
| 12 NGC 4395       | 0.1       | 743              | 44     |                      |      |
| 13 DDO169NW       | 0.0       | 635              | 24     |                      |      |
| 14 MCG+06-27-017  | 0.0       | 759              | 11     |                      |      |
to be physical, are represented by closed symbols, while the members of the suites with $-0.5 < \Theta_1 < 0$ are shown by the open symbols. The extension of the companion sample to objects with slightly negative values of $\Theta_1$ was done so as not to miss some possible physical members of the group in which the distances have so far been measured with low accuracy. The objects in this boundary category may appear to be both the real companions of main galaxies or belong to the population of the general field. Note that for the MW companions we are not listing the spatial distances but their projection on the plane perpendicular to the line of sight toward the MW center.

The middle panel of Figure 1 shows the $\{|\Delta V|, R_p\}$ distribution for 174 members of rich suites around 13 other massive nearby galaxies. Prospective physical companions with $\Theta_1 \geq 0$ ($N = 142$) are also marked here by solid symbols.

In addition to 15 rich suites, the Local Volume is composed of a lot of small suites where the radial velocities are measured in one or several presumed companions. We have combined these small suites in a composite ("synthetic") suite. The $\{|\Delta V|, R_p\}$ diagram for 107 companions uniting small suites is represented in the lower panel of Figure 1. We only kept the cases where the stellar mass of the companion does not exceed half the mass of the main galaxy.

The dashed lines in all three panels of Figure 1 show quadratic regressions of the velocity difference on the projection separation of companions. For the suites of galaxies around MW and M31, the regression has a negative slope. While for the synthetic suite of 142 companions around the 13 most massive galaxies and for the synthetic suite, uniting small suites, regressions show a weak increase in velocity dispersion from the center to the suite periphery. Different behavior of the regressions may indicate the atypical character of the motion of the MW and M31 companions in comparison to the suites of other massive nearby galaxies. Another reason for the rising part of the velocity dispersion may be caused by the presence of a large-scale halo when nearby groups form a larger structure, the Local Sheet, which would give rise to the observed enhancement of the velocity dispersion at large radii. However, a more obvious reason for this phenomenon is caused by the presence on the suite outskirts of an admixture of some false members entering the suites from the general field.

The basic characteristics of the considered suites are presented in Table 2. Its columns contain (1) the name of the suite/group by its main galaxy, (2) the number of physical ($\Theta_1 \geq 0$) members of the group with measured radial velocities, (3) the average projection separation of the companions from the main galaxy (in kiloparsecs), (4) the mean absolute value of the radial velocity difference of the companions relative to the main galaxy (in kilometers per second), (5) the main galaxy stellar mass in units of $10^{10}$ $M_\odot$, and (6) the value of orbital mass of the group (suite) with the standard error in units of $10^{12}$ $M_\odot$. The location of suites in this table corresponds to their breakdown in the three panels of Figure 1: the first lines contain the data for the MW and M31 groups, followed by the characteristics of the 13 other most populated groups of the Local Volume, and the end of the table shows the average parameters of a composite (synthetic) suite.

### Table 1 (Continued)

| Name   | $\Theta_1$ | $R_p$ | $|\Delta V|$ |
|--------|------------|-------|-------------|
| 4 IC2787 | 2.3        | 176   | 3           |
| 5 AGC251534 | 1.7      | 237   | 80          |
| 6 NGC 3593 | 0.8       | 249   | 87          |
| 7 CGCG 066-109 | 0.4     | 728   | 50          |

| Name   | $\Theta_1$ | $R_p$ | $|\Delta V|$ |
|--------|------------|-------|-------------|
| 1 KK251 | 3.5        | 59    | 78          |
| 2 UGC11583 | 3.3      | 65    | 74          |
| 3 KK252 | 3.1        | 80    | 86          |
| 4 KKR55 | 2.4        | 136   | 18          |
| 5 KKR56 | 1.7        | 238   | 91          |
| 6 Cepheus1 | 0.9      | 401   | 13          |

### Table 2

| Main Galaxy | $N_1$ | $R_p$ | $|\Delta V|$ | $M_{\ast, SM}$ | $M_{\ast, orb}$ |
|-------------|-------|-------|-------------|----------------|-----------------|
| Milky Way   | 27    | 121   | 84          | 5.0            | 1.35 ± 0.47     |
| M31         | 39    | 198   | 93          | 5.4            | 1.76 ± 0.33     |
| MW + M31    | 66    | 167   | 89          | 5.2            | 1.56            |
| N8128       | 15    | 343   | 110         | 8.1            | 6.71 ± 2.09     |
| N4594       | 6     | 577   | 153         | 20.0           | 28.47 ± 17.80   |
| N3368       | 20    | 408   | 150         | 6.8            | 17.00 ± 4.30    |
| N4258       | 11    | 316   | 96          | 8.7            | 3.16 ± 1.01     |
| N4736       | 14    | 515   | 50          | 4.1            | 2.67 ± 0.90     |
| N5236       | 10    | 294   | 57          | 7.2            | 1.06 ± 0.28     |
| N253        | 7     | 500   | 51          | 11.0           | 1.51 ± 0.59     |
| N3115       | 6     | 215   | 82          | 8.9            | 3.43 ± 2.00     |
| M101        | 6     | 167   | 76          | 7.1            | 1.47 ± 0.67     |
| IC342       | 8     | 321   | 66          | 4.0            | 1.81 ± 0.82     |
| N3627       | 7     | 254   | 69          | 10.2           | 1.45 ± 0.39     |
| N6946       | 6     | 163   | 60          | 5.8            | 0.66 ± 0.34     |
| All 13      | 142   | 332   | 96          | 8.5            | 6.27            |

| Synth all   | 89    | 188   | 69          | 2.6            | 2.74 ± 0.77     |
| Synth L     | 30    | 352   | 73          | 6.3            | 5.76 ± 2.09     |
| Synth M     | 29    | 156   | 79          | 1.3            | 2.08 ± 0.68     |
| Synth S     | 30    | 56    | 55          | 0.18           | 0.34 ± 0.13     |

**Notes.** The columns contain: (1) the name of the suite/group by its main galaxy, (2) the number of physical ($\Theta_1 \geq 0$) members of the group with measured radial velocities, (3) the average projection separation of the companions from the main galaxy (in kiloparsecs), (4) the mean absolute value of the radial velocity difference of the companions relative to the main galaxy (in kilometers per second), (5) the main galaxy stellar mass in units of $10^{10}$ $M_\odot$, and (6) the value of orbital mass of the group (suite) with the standard error in units of $10^{12}$ $M_\odot$. The location of suites in this table corresponds to their breakdown in the three panels of Figure 1: the first lines contain the data for the MW and M31 groups, followed by the characteristics of the 13 other most populated groups of the Local Volume, and the end of the table shows the average parameters of a composite (synthetic) suite.
Figure 1. Line-of-sight velocity of the suite members relative to the main galaxy as a function of their projected linear separation. The upper panel corresponds to 70 companions of the MW (squares) and M31 (diamonds). The middle panel indicates data on 174 galaxies in the 13 most populated nearby suites. The bottom panel presents a synthetic suite formed of 107 companions around other smaller Main Disturbers. Marginal members of the suites with $\Theta_1 = [-0.5 - 0.0]$ are depicted by open squares. The dashed lines trace quadratic regressions.

4. MILKY WAY AND ANDROMEDA SUITES COMPARED WITH OTHERS

Modeling the structure and kinematics of galaxy groups within the $\Lambda$CDM paradigm, many authors (Libeskind et al. 2010; Zavala et al. 2009; Knebe et al. 2011) choose the Local Group to make a comparison with the observational data. As known, the Local Group has two gravitating centers: MW and M31, which are approaching each other with a mutual velocity of about 110 km s$^{-1}$. This binary character is not an exclusive feature. For example, the neighboring groups M81 and NGC 2403, IC 342 and Maffei I, and NGC 5128 and NGC 5236 also belong to the class of binary merging groups. From the standpoint of the group mass estimate from the orbital motions of the companions, however, the listed galaxies have to be considered as standalone dynamical centers.

Previously, Karachentsev et al. (2014a) noted that judging from some morphological features, the groups of galaxies around the MW and M31 are not quite typical. This primarily refers to the presence near the MW of two companions (the Magellanic Clouds) rich in gas. There are also other features that distinguish the MW and M31 groups from other nearby ones.

Six histograms in Figure 3 represent the distributions of the 15 most populated suites in the Local Volume based on the following parameters: the average projected separation of the companions from the main galaxy, $\langle R_p \rangle$, the mean absolute
value of the radial velocity difference of the companion and the main galaxy, the logarithm of the stellar mass of the MD, the MD orbital mass, the ratio of the orbital mass to the sum of stellar masses of all the galaxies in the group, $M_{\text{orb}}/\Sigma M_*$, and the average crossing time, $t_{\text{cr}} = R_p/\sigma_v$, for the suite members, where $t_{\text{cr}}$ is expressed in terms of the age of the universe, $T_0 = 13.7$ Gyr. The groups of galaxies around the MW and Andromeda are marked with “M” and “A,” respectively.

According to these data, the linear dimension of the suites around the MW and M31 are approximately two times less extended than the typical suite of other neighboring massive galaxies. In the case of the MW, this could be caused by the obvious selection effect: most of the recently discovered ultra-low luminosity companions of the MW were found at distances of less than 100 kpc (Willman et al. 2005; Belokurov et al. 2006). To some extent, the small linear size of the suite of companions around M31 can also be caused by a selection effect since the most thorough search for new companions was carried out in a limited region around M31 (Ibata et al. 2007; Martin et al. 2009). However, the most plausible explanation of this difference may also be the presence in the suites of neighboring massive galaxies of a certain number of false members which appear on the periphery of the suites from the general field.

In contrast to the linear dimensions, the radial velocity dispersion for the companions of the MW and M31 does not stand out among the other groups (panel “b”).

The “c” histogram data show that based on their stellar masses, both the MW and M31 are not in the top 10 most massive galaxies in the Local Volume. This also may be the reason for understated linear dimensions of the suites around the MW and M31.

The “d” and “e” histograms show the distribution of 15 suites by orbital mass and by the ratio of the orbital mass-to-sum of stellar masses of the group members, respectively. The two groups located most rightward on these panels correspond to the suite around NGC 4594 (“Sombrero”) and the group NGC 3368/3379 (Leo I).

In the distribution of suites by the value of $M_{\text{orb}}$, both the MW and M31 groups are shifted toward lower values relative to the average, whereas based on the $M_{\text{orb}}/\Sigma M_*$ parameter, both groups are not significantly different from the others.

The lower panel of Figure 3 shows the distribution of suites by the average crossing time of the companions. A typical dynamic situation in the group of the Local Volume is expressed by the fact that the companions of massive galaxies have time to make about five oscillations around the center, which is sufficient for the group to get virialized. Two suites on the right side of the histogram with $t_{\text{cr}} \sim 1/2$ are the scattered groups around NGC 253 (the Sculptor filament) and NGC 4736 (the CVn I cloud), the dynamical relaxation of which has apparently not yet been achieved.

5. ORBITAL AND PROJECTED MASSES OF NEIGHBORING GROUPS

As noted above, the formation of suites around the nearby galaxies was made based on the data on mutual separations and stellar masses ($L_K$-luminosities) of galaxies in the Local Volume. Radial velocities of galaxies were not taken into account here. Among ∼400 groups from the list of MK11, there are fairly nearby groups falling into the Local Volume. In 18 of them, the number of members with known radial velocities is not too small ($N_v \geq 4$) to estimate the projected mass of
the group with an acceptable statistical error. The sample of these 18 groups presents a unique opportunity to compare the dynamical mass estimates made by applying different methods to the systems of galaxies, the principles of identification of which were essentially different.

Let us recall that the arrangement of galaxies in MK groups was carried out via the pairwise revision of all galaxies with two conditions: the total energy of a virtual bound pair must be negative, and the pair components have to be within the “zero velocity sphere,” determined by the total mass of the pair. In the space of projected separations $R_p$ and radial velocity differences $\Delta V_{12}$, these conditions are expressed as

$$\Delta V_{12}^2 R_p < 2G(M_1 + M_2),$$

$$\pi H_0^2 R_p < 8G(M_1 + M_2),$$

where the condition

$$M/M_* = \kappa = 6$$

was assumed for the relation of the dynamical mass of each galaxy to its stellar mass.

Then, all the virtually bound pairs with common members were united in a group. Unlike another widely used method of organizing the galaxies in “friends of friends” groups (Huchra & Geller 1982; Crook et al. 2007), criteria (7)–(9) contain only one arbitrary dimensionless parameter, $\kappa$. At the empirically selected value of $\kappa = 6$, criteria (7)–(9) bring about 54% of all galaxies together in pairs, groups, and clusters, which is in good agreement with the observed structure of the Local Volume (see the details in MK11).

A comparison of parameters of the suites around 18 nearby massive galaxies with the characteristics of the corresponding nearby MK groups is given in Table 3. The top rows of the table represent the data for the MK groups, while the lower rows list the parameters of the suites. The columns contain: (1) the name of the main galaxy of the group/suite, (2) the number of galaxies in the group/suite with measured radial velocities, (3) the distance to the group (in megaparsecs), determined by the mean radial velocity of the group members relative to the Local Group centroid at $H_0 = 73 \text{ km s}^{-1} \text{ Mpc}^{-1}$, and the individual distance of the principal galaxy of the suite, (4) the mean radial velocity of the group members relative to the Local Group centroid at $H_0 = 73 \text{ km s}^{-1} \text{ Mpc}^{-1}$, and the individual distance of the principal galaxy of the suite, (5) the mean square of the companion velocities relative to the main galaxy (in kilometers per second), (6) the mean harmonic radius of the group and the mean projection separation of companions from
### Table 3
Nearby Suites Common with the MK (2011) Groups

| Group | Nv | Dh | σV | Rh | log M∗ | log M∗ | log M∗/M∗ | T | ΔM12 | Θ1 | Θ5 | ΘJ |
|-------|----|----|----|----|--------|--------|------------|---|------|-----|-----|-----|
| N253  | 6  | 5.1| 87 | 275| 11.24  | 12.87  | 1.63       | 5 | 3.66 | −0.3| 0.2 | 0.7 |
|       | 8  | 3.9| 64 | 500| 11.07  | 12.18  | 1.11       |   |       |      |     |     |
| N628  | 6  | 11.4|46 | 171| 10.71  | 12.18  | 1.47       | 5 | 4.96 | −0.4| −0.2| −0.5|
|       | 5  | 7.3 | 82 | 230| 10.32  | 12.20  | 1.88       |   |       |      |     |     |
| N672  | 5  | 7.7 | 41 | 74 | 9.78   | 11.39  | 1.61       | 5 | 1.78 | 3.8  | 3.8  | 0.2 |
|       | 4  | 7.2 | 67 | 105| 9.87   | 11.66  | 1.79       |   |       |      |     |     |
| N891  | 18 | 10.6|60 | 197| 11.30  | 12.64  | 1.34       | 3 | 0.30 | −0.9 | −0.5| −0.1|
|       | 4  | 9.8 | 35 | 600| 10.96  | 11.90  | 0.94       |   |       |      |     |     |
| N2903 | 4  | 5.7 | 31 | 69 | 10.42  | 11.62  | 1.20       | 4 | 5.64 | 1.6  | 1.6  | −0.8|
|       | 5  | 8.9 | 45 | 197| 10.82  | 11.68  | 0.86       |   |       |      |     |     |
| M81   | 30 | 2.6 | 138| 102| 10.86  | 12.59  | 1.73       | 3 | 0.81 | 2.5  | 2.6  | 1.5 |
|       | 27 | 3.6 | 133| 219| 11.11  | 12.69  | 1.58       |   |       |      |     |     |
| N3115 | 5  | 6.0 | 58 | 119| 10.53  | 12.29  | 1.76       | −1| 4.17 | 2.2  | 2.5  | 0.2 |
|       | 7  | 9.7 | 113| 215| 10.96  | 12.54  | 1.57       |   |       |      |     |     |
| N3379 | 27 | 10.2|233| 179| 11.47  | 13.23  | 1.76       | 2 | 0.05 | 1.2  | 1.5  | 2.1 |
| N3368 | 21 | 10.4|175| 408| 11.13  | 13.23  | 2.10       |   |       |      |     |     |
| N3627 | 16 | 10.0|154| 408| 11.43  | 13.05  | 1.62       | 4 | 0.19 | 1.1  | 1.3  | 2.0 |
|       | 8  | 10.3| 78 | 230| 11.11  | 12.16  | 1.05       |   |       |      |     |     |
| N4258 | 15 | 7.6 | 80 | 254| 10.97  | 12.45  | 1.48       | 4 | 2.34 | 1.2  | 1.4  | 1.0 |
|       | 12 | 7.8 | 127| 316| 10.97  | 12.50  | 1.53       |   |       |      |     |     |
| N4594 | 11 | 11.7| 61 | 597| 11.53  | 12.90  | 1.37       | 1 | 2.98 | 2.7  | 2.8  | −0.4|
|       | 7  | 9.3 | 188| 577| 11.30  | 13.45  | 2.15       |   |       |      |     |     |
| N4631 | 28 | 8.7 | 90 | 243| 11.12  | 12.98  | 1.86       | 7 | 0.25 | 1.8  | 1.8  | 1.0 |
|       | 5  | 7.4 | 191| 338| 10.54  | 13.24  | 2.70       |   |       |      |     |     |
| N4736 | 5  | 4.8 | 16 | 338| 10.64  | 11.34  | 0.70       | 2 | 5.49 | −0.6 | −0.1| 0.8 |
|       | 15 | 4.7 | 66 | 515| 10.72  | 12.43  | 1.70       |   |       |      |     |     |
| N5128 | 15 | 4.1 | 94 | 402| 11.21  | 12.52  | 1.31       | −2| 0.52 | 0.7  | 1.0  | 1.6 |
|       | 16 | 3.8 | 137| 343| 11.17  | 12.83  | 1.66       |   |       |      |     |     |
| N5194 | 9  | 7.9 | 84 | 182| 11.29  | 12.93  | 1.64       | 4 | 0.12 | 0.0  | 0.4  | 1.3 |
|       | 4  | 8.4 | 53 | 167| 11.12  | 11.78  | 0.66       |   |       |      |     |     |
| N5236 | 12 | 4.4 | 77 | 149| 10.78  | 12.29  | 1.51       | 5 | 3.63 | −0.5 | 0.0  | 0.0 |
|       | 11 | 4.9 | 61 | 294| 10.87  | 12.02  | 1.15       |   |       |      |     |     |
| M101  | 6  | 5.2 | 61 | 150| 10.56  | 12.05  | 1.49       | 6 | 3.97 | 0.3  | 0.5  | 0.2 |
|       | 7  | 7.4 | 81 | 167| 10.86  | 12.17  | 1.30       |   |       |      |     |     |
| N6744 | 9  | 10.3| 78 | 229| 11.12  | 12.59  | 1.47       | 4 | 1.11 | 2.0  | 2.0  | 1.1 |
|       | 4  | 8.3 | 90 | 401| 10.94  | 12.70  | 1.75       |   |       |      |     |     |
| Mean  | 13 | 7.4 | 83 | 218| 10.94  | 12.44  | 1.50       | 3 | 2.33 | 1.0  | 1.2  | 0.7 |
|       | 9  | 7.4 | 99 | 325| 10.88  | 12.41  | 1.53       |   |       |      |     |     |

**Notes.** The columns contain: (1) the name of the main galaxy of the group/suite, (2) the number of galaxies in the group/suite with measured radial velocities, (3) the distance to the group (in megaparsecs), determined by the mean radial velocity of the group members relative to the Local Group centroid at $H_0 = 73$ km s$^{-1}$ Mpc$^{-1}$, and the individual distance of the principal galaxy of the suite, (4) the dispersion of radial velocities in the group and the mean-square difference of the companion velocities relative to the main galaxy (in kilometers per second), (5) the mean harmonic radius of the group and the mean projection separation of the companions from the main galaxy (in kiloparsecs), (6) the logarithm of the total stellar mass of the group or a suite (in $M_\odot$), (7) the logarithm of the projected mass of the group and the orbital mass of the suite (in $M_\odot$), (8) the ratio of the projected/orbital mass to the total stellar mass on a logarithmic scale, (9) the morphological type of the main galaxy on a de Vaucouleurs scale, (10) the difference between the apparent K magnitudes of the first and second members of the group, and (11–13) the tidal indices, characterizing the density of the environment of the main galaxy of the group; here the $\Theta_1$ index, determined by Equation (6), expresses the contribution of the most significant neighbor, the $\Theta_5$ index accounts for the effect of five important neighbors, while the $\Theta_J$ index corresponds to the logarithm of the stellar density contrast in a sphere of 1 Mpc radius around the main galaxy taken with respect to the mean cosmic density.
the main galaxy (in kiloparsecs), (6) the logarithm of the total stellar mass of the group or the suite (in \(M_\odot\)), (7) the logarithm of the projected mass of the group and the orbital mass of the suite (in \(M_\odot\)), (8) the ratio of the projected (or orbital) mass-to-total stellar mass on a logarithmic scale, (9) the morphological type of the main galaxy on a de Vaucouleurs scale, (10) the difference between the apparent K magnitudes of the first and second members of the group, and (11–13) the tidal indices, characterizing the environment density of the main galaxy in the group; here the \(\Theta_1\) index, determined by Equation (6), expresses the contribution of the most significant neighbor, the \(\Theta_2\) index accounts for the effect of five important neighbors, and the \(\Theta_3\) index corresponds to the logarithm of stellar density contrast in a sphere of 1 Mpc radius around the main galaxy taken with respect to the mean cosmic density. The last line in the table shows the mean values of the considered quantities. Note that the luminosity of the brightest suite member does not exceed one-fourth of the MD’s luminosity for 10 of the 15 suites, which justifies the consideration of suite galaxies as test particles orbiting around the central massive body.

One can note that Table 3 has no data on the groups around IC 342 and NGC 6946. They are not included in the list of MK groups because they are located in the zone of strong Galactic extinction. The groups of companions around the MW and M31 are also missed because their distances based on the mean radial velocities of the galaxies, used by Makarov & Karachentsev (2011), would have no physical meaning. A comparison of the Table 3 data on the groups versus the suites reveals the following properties.

1. The total number of galaxies in the MK groups, 227, is comparable to the total number of physical members of the suites: 170 at \(\Theta_1 > 0\) and 224 at \(\Theta_1 > -0.5\). Consequently, the grouping of galaxies into suites according to the zones of gravitational influence around dominant galaxies and the MK criteria (7)–(9) have approximately the same clustering efficiency rate. However, the data presented also reveal significant individual differences in the populations of groups and suites. For example, in the NGC 891, NGC 4631, and NGC 4736 groups, this ratio amounts to 18:4, 28:5, and 5:15, respectively. The greatest differences are typical for the scattered groups (suites), where the second member of the group by luminosity competes with the MD.

2. The mean radial velocity dispersion in groups, equal to 83 km s\(^{-1}\), and the mean square velocity difference of the companions in the suites, amounting to 99 km s\(^{-1}\), are in reasonable agreement with each other. In other words, condition (7) in the MK criteria does not possess strong selectivity against the pairs of galaxies with a large radial velocity difference.

3. The difference between the Hubble distance to the groups, \(D_H = (V_L/G)/H_0\), and the individually measured distance to the main galaxy of the suite, \(D_{MD}\), is generally small: 7.44 Mpc and 7.39 Mpc, respectively. While in some groups, for instance, in NGC 628 and NGC 2903, these distances differ by half (due to the bulk motions toward the Virgo cluster), which affect the luminosity of the group and influences the number of clustered members in it.

4. Individual differences between the estimates of the projected mass and orbital mass are quite large. In the case of groups of galaxies around NGC 253, NGC 891, NGC 3627, NGC 4594, NGC 4736, and NGC 5194, these differences exceed a factor of three. Nevertheless, the average values of \((\log M_p) = 12.44\) and \((\log M_{orb}) = 12.41\) for an ensemble of 18 groups/suites are in good agreement with each other. Similarly, the average ratios of \((\log(M_p/\Sigma M^*)) = 1.50\) and \((\log(M_{orb}/\Sigma M^*)) = 1.53\) do not show any significant systematic difference, although in some groups/suites these ratios differ significantly. In addition to random factors caused by the poor statistics, the differences in the estimates of \(M_{orb}\) and \(M_p\) occur more in scattered groups, where we can discern the substructures around the galaxies, which are only slightly less massive than the main member of the group. The examples revealing the presence of such hierarchical substructures can be found in the NGC 891/NGC 925, NGC 3368/NGC 3379, and NGC 5194/NGC 5055 groups.

5. The data in the last columns of Table 3 show that the density of the group environment, the difference in the apparent magnitudes of the two brightest members of the group, and the morphological type of the main galaxy do not affect the ratio of dark-to-luminous matter in the group in a substantial way.

It should be emphasized that the above derived agreement between the typical values of orbital and projected masses in the Local Volume, \(M_{orb} \approx M_p \approx 33 M^*\), is not a trivial one. The UNGC contains approximately the same number of radial velocities as what was used by MK11 within \(D < 11\) Mpc. However, the UNGC has much more data on galaxy distances than the MK11 sample. Actually, MK11 estimated distances to a group via the average redshift of its members burdened by peculiar velocities and local streams. This does not matter in the case of the UNGC, which collected hundreds of accurate individual distances. Another significant difference is caused by different algorithms applied to the galaxy grouping. To find a group, MK11 used separations and luminosities of galaxies as well their radial velocities. In the case of UNGC, only 3D separations and luminosities (but not redshifts) were used to identify a suite of companions around a dominant galaxy. We cannot state that one finding algorithm is better (or objective) than the other, but they both yield almost the same average ratio \(M_{DM}/M^*\) for the small local structures.

6. ORBITAL-TO-STEMALL MASS RATIOS

The orbital mass estimates for the populated suites, shown in Tables 2 and 3, were determined by the suite members with tidal indices \(\Theta_1 \geq 0\). Obviously, the choice of the maximum value of \(\Theta_1\), based on which the galaxies were included in the suite, affects the number of members of the suite, their total luminosity, and the orbital mass estimate. With large positive values of \(\Theta_1\), many physical companions of the MD do not make it into this suite. The orbital mass would in this case prove to be underestimated. On the contrary, inclusion of galaxies with arbitrary negative values of \(\Theta_1\) in the suite contributes to its pollution by false members from the general field, thus leading to an overestimation of the \(M_{orb}\).

Figure 4 shows how sensitive the \(M_{orb}/\Sigma M_*\) estimates are to the choice of the threshold value of \(\Theta_1\) for the 15 most populous groups in the Local Volume. The variations in the \(M_{orb}/\Sigma M_*\) ratio depending on \(\Theta_1\) in the range of \([-0.5 < \Theta_1 < 0.5]\) with increments of 0.1 are shown in this figure for each of the 15 suites.

We can see from these tracks that a rapid growth of \(\log(M_{orb}/\Sigma M_*)\) toward negative values of \(\Theta_1\) takes place in only five suites: NGC 253, NGC 4258, NGC 4594, NGC 4736, and NGC 5236. In the remaining groups (suites), the ratio of the
Figure 4. Ratio of orbital mass to the sum of stellar mass for the 15 richest suites as a function of cutoff on $\Theta_1$. The suites of the MW and M31 are marked by solid diamonds and squares, respectively. The log-of the suites around the MW and M31, which are marked in the variation of orbital mass to the sum of stellar masses is weakly responsive to Figure 4.

According to Jones et al. (2006), the mean density of the stellar mass amounts to $j_s = 4.28 \times 10^9 (M_\odot / \text{Mpc}^3)$ at $H_0 = 73 \text{ km s}^{-1} \text{ Mpc}^{-1}$. Assuming $M_\odot / L_K = 1 M_\odot / L_\odot$ (Bell et al. 2003), the mean cosmic density of matter $\Omega_m = 0.28$ in the standard $\Lambda$-CDM model is expressed as $M_{\text{DM}} / M_* = 97$. This value is shown in Figure 4 by the dashed horizontal line. As one can see, all the groups (suites), except for NGC 3368 (Leo I) and NGC 4594 ("Sombrero"), have $M_{\text{DM}} / \Sigma M_*$ below this value. Consequently, the amount of dark matter in the suite volumes around the massive nearby galaxies is clearly not enough to provide the cosmic density $\Omega_m = 0.28$.

The upper panel of Figure 5 shows the distribution of the 18 most populated nearby groups given in Table 3 by their total stellar masses and the projected mass estimates. The solid line corresponds to the cosmic value of $M_{\text{DM}} / M_* = 97$. As one can see, all the nearby groups are located below the $\Omega_m = 0.28$ line, following the value which is about three times lower (dashed line).

A similar diagram for the orbital mass estimates of the suites is shown at the bottom panel of Figure 5. Each of the 15 populated suites (Table 2) is shown by a circle with a vertical bar, corresponding to the standard error of $M_{\text{orb}}$. The solid and dashed lines are fixing the values of $M_{\text{DM}} / M_* = 97 (\Omega_m = 0.28)$ and 31 ($\Omega_m = 0.09$), respectively. The major part of the suites is concentrated near the line of $\Omega_m = 0.09$ and only two suites, NGC 3368 and NGC 4594, reside above the $\Omega_m = 0.28$ line. In addition to the 15 populated suites, three small diamonds in the figure show the average values of $\langle M_{\text{orb}} / \Sigma M_* \rangle$ for the synthetic suites, L, M, and S, the data on which are listed at the bottom of Table 2. Synthetic suites around the galaxies with small (S) and medium (M) masses are characterized by a high $\langle M_{\text{orb}} / \Sigma M_* \rangle$ ratio, and within the error they lie on the line of $\Omega_m = 0.28$.

Among the smallest suites, isolated pairs of dwarf galaxies can be found, where each component of the pair is the MD for the second component. The list of such 12 dwarf pairs is presented in Table 4. The low luminosity of these galaxies clearly does not favor their detection outside the Local Volume. Nevertheless, the catalog of binary galaxies in the Local Supercluster by Karachentsev & Makarov (2008) as well as the list of multiple dwarfs by Makarov & Uklein (2012) contain about 50 more similar dwarf pairs.

The binary systems in Table 4 are listed by their distance from us. The table columns represent the following data, adopted from the UNGC catalog: (1) names of the components, (2) the distances (in megaparsecs), (3) the tidal indices, characterizing the degree of mutual gravitational influence, (4) the logarithm of the stellar mass ($M_\odot$), (5) the logarithm of the hydrogen mass ($M_\odot$), (6) the radial velocity difference between the components (in kilometers per second), (7) the velocity measurement error (in kilometers per second), (8) the projected separation (in kiloparsecs), and (9) the logarithm of the orbital mass ($M_\odot$). According to these data, the average orbital mass of dwarf pairs amounts to $1.83 \times 10^{11} M_\odot$, and the average sum of the stellar masses of the components is $7.7 \times 10^8 M_\odot$. The ratio of these
Figure 5. Upper panel: the projected mass of nearby groups as a function of the sum of their stellar masses. Some individual groups are marked by the name of their principal member. The diagonal solid and dashed lines indicate the ratios: \( \frac{M_{\text{DM}}}{M_*} = 97 \) and 31, respectively. Bottom panel: the orbital mass of nearby suites vs. the sum of their stellar masses. Solid circles with error bars correspond to individual rich suites. The suites around the MW and M31 are marked by crosses. Small solid diamonds with error bars indicate the weighted mean ratios for the synthetic suites divided into three sets: L (large), M (medium), and S (small) according to their Main Disturber masses. The filled square indicates the weighted average ratio for 12 isolated pairs of dwarfs. The open and filled large diamonds show the total orbital and stellar masses for the Local Volume with a radius of the 10 Mpc and 8 Mpc, respectively. The diagonal lines are the same as those in the upper panel.

quantities \( \langle \frac{M_{\text{orb}}}{(M_* + M_{\text{gas}}^*)} \rangle = 237 \pm 172 \) is shown in the lower panel of Figure 5 by a square. The position of the square above the \( \frac{M_{\text{DM}}}{M_*} = 97 \) line (but with a large error bar) gives an impression that the dark-to-baryonic matter ratio tends to be higher in the low-luminosity galaxies than in the galaxies with normal luminosities. This assertion has been repeatedly stated in the literature (Mateo 1998; Moster et al. 2010).

However, we should pay attention to two important circumstances here. The orbital mass estimates using Equation (4) are statistically biased ones. In the presence of radial velocity measurement errors, the product \( (\Delta V_t^2 \times R_{p12}) \) in (4) should be replaced by \( (\Delta V_t^2 - \sigma_{v1}^2 - \sigma_{v2}^2) \times R_{p12} \). Accounting for the contribution of \( \sigma_{v1}, \sigma_{v2} \) errors lowers the average ratio of \( \langle \frac{M_{\text{orb}}}{\Sigma M_*} \rangle \) to 214 \( \pm 155 \).

Comparison of stellar versus hydrogen masses of dwarf galaxies in pairs shows that these values are comparable with each other. The mean difference \( \langle \log M_h - \log M_* \rangle \) from the Table 4 data is equal to \(-0.13\). It becomes positive, +0.14, if one takes into consideration that the mass of gas accounting for helium and molecular hydrogen is on average 1.85 times larger than the mass of atomic hydrogen (Fukugita & Peebles 2004). Having introduced both corrections, the ratio of the orbital mass to the sum of baryonic masses of the pairs drops to

\[ \langle \frac{M_{\text{orb}}}{\Sigma (M_* + M_{\text{gas}})} \rangle = 78 \pm 56 \]

Summing the stellar masses in all the considered suites of the Local Volume, we obtain \( \Sigma M_* = 1.52 \times 10^{12} M_\odot \). With the average local stellar mass density of \( j_* = 6.0 \times 10^6 M_\odot/\text{Mpc}^3 \) (Karachentsev et al. 2013) and \( M_*/L_K = 1 M_\odot/L_\odot \), a sphere with a 10 Mpc radius contains the total stellar mass of \( 1.88 \times 10^{12} M_\odot \) (a small correction is introduced here, accounting for the zone of interstellar extinction in the Milky Way). Therefore, the studied suites contain 80% of the total
Table 4
Isolated Binary Dwarfs

| Name       | D   | O_1 | log M_4 | log M_H1 | ΔV | σv | R_P | log M_orb |
|------------|-----|-----|---------|----------|----|----|-----|-----------|
| N3109      | 1.32| 0.2 | 8.57    | 8.37     | 44 | 2  | 27  | 10.04     |
| Antlia     | 1.32| 2.3 | 6.47    | 5.92     | 1  |    |     |           |
| Dwing2     | 3.0 | 2.8 | 8.35    | 8.01     | 35 | 2  | 13  | 10.27     |
| MB3        | 3.0 | 3.0 | 8.09    | 7.78     | 1  |    |     |           |
| KKR 59     | 5.9 | 1.7 | 9.16    |          | 11 | 4  | 36  | 9.70      |
| KKR 60     | 5.9 | 2.5 | 8.42    |          | 7  |    |     |           |
| ESO121-20  | 6.0 | 0.1 | 7.78    | 7.94     | 33 | 5  | 6   | 9.85      |
| LVO615-71  | 6.0 | 0.6 | 7.07    | 7.36     | 4  |    |     |           |
| UGC2716    | 6.4 |      | 8.34    | 7.68     | 29 | 1  | 112 | 11.04     |
| UGC2684    | 6.5 |      | 7.57    | 7.92     | 4  |    |     |           |
| KUG1202268 | 6.7 | 0.1 | 7.70    |          | 4  | 33 | 16  | 8.49      |
| LV1205281  | 6.7 | 0.5 | 7.37    |          | 14 |    |     |           |
| DDO 64     | 7.1 | 1.6 | 8.04    | 8.24     | 18 | 2  | 4   | 9.21      |
| KK 78      | 7.1 | 2.8 | 6.92    | 7.35     | 4  |    |     |           |
| DDO161     | 7.3 | 1.5 | 8.91    | 8.99     | 10 | 18 | 40  | 9.67      |
| UGCA319    | 7.3 |      | 8.22    | 7.97     | 4  |    |     |           |
| MAPS1206+3 | 7.4 | 0.4 | 7.81    |          | 4  | 27 | 44  | 8.92      |
| LV12073+133| 7.4 | 0.2 | 7.12    |          | 4  |    |     |           |
| NGC1156    | 7.8 |      | 9.31    | 8.82     | 64 | 1  | 80  | 11.58     |
| LV030035   | 7.8 |      | 7.34    | 6.20     | 3  |    |     |           |
| NGC1744    | 10.0| 0.1  | 9.42    | 9.35     | 90 | 2  | 169 | 12.20     |
| ESO486-214 | 10.0| 0.8  | 8.74    | 8.47     | 18 |    |     |           |
| KK 94      | 10.4| 2.3  | 7.34    | 7.69     | 12 | 1  | 7   | 9.08      |
| LeG 21     | 10.4| 2.8  | 6.90    | 7.09     | 1  |    |     |           |

Notes. The table columns represent the following data, adopted from the UNGC catalog: (1) the names of the components, (2) their distances (in megaparsecs), (3) the tidal indices, characterizing the degree of mutual gravitational influence, (4) the logarithm of stellar mass (M_⊙), (5) the logarithm of the hydrogen mass (M_HI), (6) the radial velocity difference of the components (in kilometers per second), (7) the velocity measurement error (in kilometers per second), (8) the projected separation (in kiloparsecs), (9) the logarithm of orbital mass (M_orb).

Their location with respect to the Local Sheet. Obviously, these groups need a more comprehensive, special analysis of their structure and kinematics with the use of new observational data.

It should be added that out of six members of the NGC 4594 suite, one galaxy, DDO 148, resides at the large projected distance of 1.1 Mpc from the Sombrero galaxy, having a radial velocity difference of 276 km s⁻¹. The contribution of DDO 148 to the total orbital mass estimate of the Sombrero suite is more than a half. Since the distance to DDO 148, D = 9.0 Mpc, is determined by the Tully–Fisher method with an error of ±2 Mpc, a more accurate estimate of its distance can dramatically change the value of M_orb for this suite.

If we limit the Local Volume by the 8 Mpc radius, excluding a still uncertain situation on the far boundary, the ratio of the total orbital mass of all the suites in this volume to the sum of stellar masses will be ΣM_orb/ΣM_* = 30 at M_*/L_K = 1 M_⊙/L_⊙. On the lower panel of Figure 5, this value, falling on the Ω_m = 0.09 line, is marked by a large solid diamond.

7. Masses Derived from the Hubble Flow Around the Nearby Groups

A high density of observational data on the radial velocities and distances of galaxies in the Local Volume provides an opportunity to determine the masses of nearby groups not only by their virial motions, but also by perturbations of the Hubble flow around them. This idea was proposed by Lynden-Bell (1981) and Sandage (1986) and is based on the measurement of the radius of the zero velocity sphere R₀ which separates a group (or a cluster) from the surrounding volume that expands.

In the standard cosmological model with parameters H_0 = 73 km s⁻¹ Mpc⁻¹ and Ω_m = 0.24 (Spergel et al. 2007), the total mass of a spherical overdensity is expressed as

\[ M_T/M_⊙ = 2.12 \times 10^{12} \times (R₀/\text{Mpc})^3. \] (10)

An important circumstance here is that the estimate of the total mass of a group corresponds to the scale of R₀, which is \~3.7 times larger than its virial radius.

The analysis of observational data on radial velocities and separations of galaxies in the vicinity of the Local Group and other nearby groups was done by different authors. A summary for six groups is presented in Table 5. The columns of the table list: (1) the name of the group, (2) the logarithm of the orbital mass of the group in units of solar mass and its error, (3) the radius of the zero velocity sphere (in megaparsecs) and its error, (4) the logarithm of the total mass of the group, determined by Equation (10) and its error, (5) the difference between the total and orbital mass estimates, and (6) the reference to the source of data on R₀.

In general, the estimates of mass by two independent methods agree with each other quite well. However, a moderate systematic difference of mass estimates in favor of the orbital masses is noteworthy. For six groups, the mean difference amounts to (Δlog(M_T/M_orb)) = −0.20 ± 0.05. This paradoxical result, lying in the fact that the estimates of the total mass of the groups on a scale of R₀ = 3.7R₀ are lower than the orbital (as well as the projected) mass estimates on a scale of the virial radius R_v, might have a simple interpretation. Chernin et al. (2013) noted that the estimate of the total mass of a group includes two components: M_T = M_M + M_DE, where M_M is the mass of the dark and baryonic matter, and M_DE is the mass, negative...
in magnitude, determined by the dark energy with a density of \( \rho_{DE} \):

\[
M_{DE} = (8\pi/3) \times \rho_{DE} \times R^3.
\]

On a scale of \( R_0 \), the contribution of this component to the group mass is small, not exceeding 1%, but in a sphere of \( R_0 \) radius, the role of this "mass defect" becomes significant. In the standard \( \Lambda \)CDM model with \( \Omega_m = 0.24 \), the contribution of dark energy is

\[
(M_{DE}/M_\odot) = -0.85 \times 10^{12} \times (R_0/\text{Mpc})^3,
\]

i.e., about 40% of the value determined by Equation (10). A correction to the total mass by a factor of 1.4 can almost completely eliminate the observed discrepancy between the group mass estimates at different scales.

In turn, such an agreement of mass estimates by the internal and external motions after the correction for the dark energy component can be interpreted as further empirical evidence for the existence of the dark energy itself appearing in the dynamics of nearby groups.

### 8. CONCLUDING REMARKS

The high-density data on the distances and radial velocities of the \( \sim 800 \) most nearby galaxies from the UNGC provides a unique opportunity to investigate the distribution of light and dark matter in the Local Volume of \( \sim 10 \) Mpc radius in outstanding detail. The analysis of these data shows that about half of the population of the Local Volume is concentrated in the rooms, dominated by the gravitational influence of only the 15 most massive galaxies. Ranking the galaxies by magnitude of tidal force allows one to group small galaxies into suites around their Main Disturbers. Assuming Keplerian motions of the companions around the central galaxy with a typical orbit eccentricity of \( e^2 = 1/2 \), we have determined the orbital masses of the main galaxies in the Local Volume, as well as the total mass of less populated suites wherein we did not use any restrictions on the radial velocities of companions relative to their main galaxies in the suites.

For the mass of the dark halo around the MW and around M31, we have obtained values of \( 1.35 \pm 0.47 \) and \( 1.76 \pm 0.33 \) in units of \( 10^{12} \, M_\odot \), respectively. Analyzing the mass estimates of these galaxies, made by various authors and via different methods, Shull (2014) has concluded that the virial masses of the MW and M31 amount to \( 1.6 \pm 0.4 \) and \( 1.8 \pm 0.5 \times 10^{12} \, M_\odot \), which is in remarkable agreement with our estimates. The total mass of the Local Group from our data is \( (3.1 \pm 0.6)(\times 10^{12} \, M_\odot) \). This estimate is consistent with the (MW + M31) mass estimates by Partridge et al. (2013) and Gonzalez et al. (2013), which were obtained based on the timing argument.

Within the Local Volume, there are 18 groups identified with the suites, for which MK11 estimated the virial (projected) masses \( M_\odot \). On average, the agreement between the orbital and projected mass estimates for the suites and groups proves to be quite satisfactory. The typical ratio of both the orbital and the projected mass to the sum of stellar masses of galaxies forming the group amounts to \( M_{\text{orb}}/M_\ast \approx 30 \).

Among the smallest suites in the Local Volume, there are 12 isolated dwarf pairs, where each galaxy with a characteristic stellar mass of \( \sim 10^8 \, M_\odot \) is the MD for the second component. The average ratio of the orbital mass to the sum of all masses for them, \( M_{\text{orb}}/M_\ast = 237 \pm 172 \), looks to be a little more than that for the suites around luminous galaxies. However, taking into account a significant gas component in these small binary systems leads to the baryonic ratio of \( M_{\text{orb}}/(M_\ast + M_{\text{gas}}) = 78 \pm 56 \), which is close to the typical one for galaxies with normal luminosities.

The distortion in the Hubble flow, observed around the six most nearby groups, allows us to determine their total masses. Independent estimates of total masses via the radius of the zero velocity sphere \( R_0 \) are slightly lower than the orbital and virial values. This difference may be due to the local effect of dark energy, which affects the kinematics of the galaxy groups, especially scattered ones.

The data we have obtained on the orbital masses of suites/groups, summed over the Local Volume of 8 Mpc radius, yield a ratio of dark to luminous matter of \( \Sigma M_{\text{orb}}/\Sigma M_\ast \approx 30 \), which corresponds to the mean local density of \( \Omega_m \approx 0.09 \). It seems difficult to indicate the precise error of this value because the error is rather dominated by systematic effects than by random statistics. The present result is in line with the measurement \( \Omega_m = 0.08 \pm 0.02 \), derived by MK11 within a volume of the Local Supercluster (\( D < 50 \) Mpc) using an independent approach to find galaxy groups. Therefore, a threefold divergence between the local and global values of \( \Omega_m \), noted by many authors, remains an unsolved mystery of the near-field cosmology.

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