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Dark matter in the Local Group

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The observational properties of galaxies accumulated in the Updated Nearby Galaxy Catalog (UNGC) were used by us to derive an orbital mass of the Milky Way and Andromeda galaxy (M 31) via motions of their 31 and 39 companions, respectively. The ratio of the orbital mass of galaxies, which is a measure of dark matter, to their stellar mass is ~ 30. If this value is taken as the average value in the Universe, then in the standard cosmological ΛCDM models it will match the value $\Omega_m \approx 0.09$ instead of the generally accepted value $\Omega_m \approx 0.28$. Taking into account that this last value is realised only in rich clusters, and that the cluster at hand contains only 10% of the total number of galaxies (while the rest are in groups or field galaxies), our results confirm the well-known problem of "lack of dark matter" in the Local group.

Key words: cosmology: dark matter - galaxies: groups: general

INTRODUCTION

One of the unresolved problems of cosmology is the nature of dark matter (DM) distribution relative to the visible (stellar) matter. Numerous studies show that the ratio $M_{\rm DM}/M_*$ of the DM mass $M_{\rm DM}$ to the stellar mass M_* of groups and clusters of galaxies increases with the size and habitability of systems. In the richest galaxy clusters such as Coma the ratio $M_{\rm DM}/M_*$ reaches two orders of magnitude. If all galaxies were part of clusters, DM associated with them would provide the average cosmic density of matter $\Omega_m \approx 0.26$ [1], corresponding to the standard cosmological ΛCDM model. However, rich clusters comprise only 10% of all galaxies; while the majority of galaxies are part of different multiplicity groups forming the filamentary structure of the "cosmic spiderweb". Summation of virial mass of groups and clusters in a volume of radius 50 Mpc have given a local density estimation $\Omega_m \cong 0.08 \pm 0.02$ [12] that is less than three times the global average density. The low values of the local density were confirmed by other authors [14, 15]. It is believed that the reason for this is the "biasing effect": when DM is distributed not as strongly concentrated as the light. The darker cluster peripheries and groups contain, possibly, large amounts of DM. This seemed to eliminate the "lost DM" paradox.

However, the assumption of massive dark halos existing around clusters and groups of galaxies is not confirmed by the observations. In [9] it was shown that the total mass of the Virgo cluster, $M_T = (8.0 \pm 2.3) \times 10^{14} M_\odot$, defined within the radius R_0 of zero velocity surface, was consistent with virial mass $M_\nu = (7.0 \pm 0.4) \times 10^{14} M_\odot$ within the virial radius R_ν. Since $R_0 \approx 3.5 R_\nu$, then this result is an evidence against significant accumulation of dark mass in the layer from R_ν to R_0. New observational data should be sought to explain the paradox of "lost DM".

This paper presents the results of estimation of the total mass of the Milky Way (MW) and the Andromeda galaxy M 31 as well as their ratios to stellar mass with the aim to confirm or refute the paradox of lost DM within the Local Group, using the newest and most complete (at the present time) data of the UNGC catalogue (Updated Nearby Galaxy Catalog) [8]. This catalogue is currently the most representative and homogeneous sample of nearby galaxies, for the majority of which spatial coordinates, luminosity, and linear velocity along the line of sight are known.

ESTIMATION OF GALAXY MASSES FROM KINEMATIC OF THEIR SATELLITES

In recent years many papers with estimates of the mass of our galaxy MW, M 31, and the Local Group (LG) as a whole, were published. Despite the proximity, physical and geometrical properties of the DM halo in MW and M 31 remain largely undefined. Even the question of which of them has greater mass is not yet clear. The distribution of DM relative to the visible stellar matter also remains an unsolved problem.

Mass determination of the galaxy groups using their radial velocities and projected distances is one of the classic tasks of extragalactic astronomy. Bahcall & Tremaine proposed [2] a method based on the concept of projection mass $q = G^{-1} V_h^2 R_p$, where

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V_h is the radial component of velocity relative to the centre of the galaxy group, R_p is the relative projection distance in the picture plane, G is the gravitational constant. They have shown that for a spherically symmetric system the average value q is: $\langle q\rangle = \pi M(3-2\langle e^2\rangle)/32$. Thus, an estimation of the galaxy group mass as a function of the average square eccentricity of orbits is:

$$M_p = \frac{32}{\pi G}(3-2\langle e^2\rangle)^{-1}\langle V_h^2 R_p\rangle. \quad (1)$$

When one galaxy, which is surrounded by "suite" of dwarf satellites, predominates by mass in a group ("patron" of group), estimate (1) is called the orbital mass. Average square eccentricity varies by a factor of 3 between the purely radial ($e = 1$) and purely circular ($e = 0$) orbits. We adopt $\langle e^2\rangle = 1/2$, which is the case for an isotropic distribution of velocities in the orbits with different eccentricities [3]. Then, from (1), the following orbital mass estimate of group was obtained:

$$M_{\rm orb} = \frac{16}{\pi G}\langle V_h^2 R_p\rangle, \quad (2)$$

where V_h and R_p are taken with respect to velocity and location of the "patron". In this paper, the expression (2) is used for assessing the "full" mass MW and M 31.

OBSERVATIONAL DATA

Observational data (equatorial coordinates, stellar mass, radial velocity, and distances) were taken from the UNGC catalogue [8]. A complete list of "suit" of giant galaxies within the Local volume was taken by us from [6]. When drawing up, its tidal index was used (from UNGC), defined as follows:

$$\Theta = \max\lfloor \log(M_n^*/D_n^3)\rfloor + C, \quad n = 1,\ldots,N. \quad (3)$$

Here M_n^* is the stellar mass of neighbouring n-th galaxy, D_n is its spatial distance from the galaxy in question. Stellar mass M^* of galaxies is measured by their L_K luminosity in the K-band with the adoption $M^*/L_K = 1\cdot M_\odot/L_\odot$. The constant $C = -10.96$ in (3) was chosen in such a way that the galaxy with $\Theta = 0$ was located at the "zero velocity sphere" relative to its main galaxy. Zero value of Θ divided the potential satellites into gravitational associated with the "patron" ones ($\Theta \geq 0$), and field galaxies ($\Theta < 0$). For MW and M 31, 27 and 39 members, respectively, of the suites that have the necessary data for calculations, were discovered. Since the errors of observational data "blur" the boundary between gravitationally bound companions and field galaxies, we used the advanced samples of satellites determined by the condition $\Theta \geq -0.5$. In the expanded sample 31 and 39 galaxies were included for MW and M 31, respectively. (For M 31 the number has not increased). It is worth to note that the previous estimation of the Local Group total mass was conducted by radius of zero velocity surface using 30 dwarf satellites [7].

Fig. 1 shows a two-dimensional distribution of MW and M 31 satellites for projected onto the picture plane distance from the "patron", R_p, and the module of relative radial velocity, $|V_h|$. Solid squares mark the position of 27 MW satellites; outlined squares mark the position of four additional satellites of MW with $0 > \Theta \geq -0.5$. Solid diamonds mark the position of 39 M 31 satellites. The dashed line shows a quadratic approximation of the dependence $|V_h|$ on R_p for the pooled sample of ML and M 31 "physical" satellites. As should be expected, MW "non-physical" satellites, on the average, are on distribution "tail" for the projected distance.

It is worth to note that physical M 31 satellites are, on average, at larger projected distances from the "patron" than MW satellites (198 kpc vs. 121 kpc). This may be due to the effect of selection because more distant MW satellites may be scattered across the sky, and thus not yet observed by the researchers. In contrast, M 31 satellites are located in a compact area around it, making them much easier to be observed.

For M 31 $M^*_{\rm M\,31} = 5.4\times 10^{10} M_\odot$ was adopted by us in accordance with UNGC [8]. For MW we adopted $M^*_{\rm MW} = 5.0\times 10^{10}$ [13]. The stellar mass of satellites (with luminosity L_K) was taken from [8].

ORBITAL MASS: RESULTS

In accordance with (2) the following values of orbital masses were obtained:

$$M^{\rm orb}_{\rm MW} = (1.35\pm 0.47)\times 10^{12} M_\odot,$$
$$M^{\rm orb}_{\rm M\,31} = (1.65\pm 0.33)\times 10^{12} M_\odot. \quad (4)$$

Simple mass addition gives the value of the Local group mass:

$$M_{\rm LG} = (3.0\pm 0.6)\times 10^{12} M_\odot. \quad (5)$$

To demonstrate the robustness of the obtained values of orbital masses, in Fig. 2 their dependence on the tidal index, the value of which varies from -0.5 to 0.5 in increments of 0.1, is shown. Solid squares indicate the estimates for MW, solid diamonds — for M 31. For convenience, the positions of the points for M 31 are shifted by 0.02 downward. Limiting by the value of $\Theta_{\rm lim} = 0$, we can, as a result of errors in the distances measuring and the differences of radial velocities, either add to "suite" the field galaxy with actually negative Θ, or reject the galaxy with actually positive Θ, physically associated with the "patron".

It is evident that our estimates are relatively stable: the variations of limited tidal index give the fluctuations of orbital mass for MW, which are lower than 14%, and lower than 4.3% for M 31.

The issue of the exact mass ratio of MW and M 31 is still unclear. According to the data mentioned above, both "full" and stellar masses of M 31 are somewhat larger than the MW masses. However, the fact that the orbital mass of MW was determined (due to the selection effect) for shorter distances ($\langle R_p \rangle \approx 120\,\mathrm{kpc}$) than that of M 31 ($\langle R_p \rangle \approx 200\,\mathrm{kpc}$) must be taken into account. Therefore, the mass ratio may be the opposite.

To compare our estimates with those of other authors, we refer the reader to [13]. Here, we present only the compilative mass estimates of MW and M 31 from this work, based on a large number of evaluations of different authors using different methods: $M_{\mathrm{MW}} = (1.6 \pm 0.4) \times 10^{12} M_{\odot}$ and $M_{\mathrm{M\,31}} = (1.8 \pm 0.5) \times 10^{12} M_{\odot}$. As can be seen, the data coincide sufficiently, considering errors.

ORBITAL MASS FOR "SYNTHETIC" MW

To check the stability of orbital mass estimations for the MW, the analogues method was used, developed in [4] for the LG. The authors of this study have chosen an analog population of the LG from cosmological simulations "Bolshoi", carried out within the ΛCDM cosmology [10], and used the observed properties of LG to obtain the probability distribution for its total mass.

In our version of the study the "natural" MW analogues were used, which were found in the "suites" in the Local Volume (LV). The simple criterion for selection to the analogues list was that the difference between the stellar mass of MW and its analogues should not exceed 1.5. In total 15 analogues were found, which in fact were suites around the galaxy M 31, NGC 3368, NGC 4736, NGC 5236, NGC 2903, NGC 2683, NGC 6744, M101, IC 342, NGC 2784, Maffei 2, NGC 6946, NGC 4945, NGC 5195, and M82. However, some of the suites contained galaxies with stellar masses on the order of that of the "patron". These members of the suite we rejected. In total, 144 galaxies with $\Theta \geq 0$ were included in the "synthetic suite".

Satellite distribution of the "synthetic MW" in the plane (R_p, $|V_h|$) is shown in Fig. 3. Solid and outlined squares correspond to the "physical" ($\Theta \geq 0$) and "non-physical" ($0 > \Theta \geq -0.5$) satellites, respectively.

As a result, the orbital mass of the"synthetic" Milky Way was obtained:

$$M^{\mathrm{orb}}_{\mathrm{MW,synth}} = (1.58 \pm 0.20) \times 10^{12} M_{\odot}$$

This value is grater than the estimation (4) for own MW satellites. It is evident that due to the greater statistics, the formal error of the orbital mass is much lower.

MASS-LUMINOSITY RATIO

Dark matter content is characterised by using the ratio χ of orbital mass to stellar mass, $\chi = M_{\mathrm{orb}} / \sum M^{*}$. The stellar mass sums of "patrons" and their satellites for MW and M 31 respectively are:

$$M^{*}_{\mathrm{MW+sat}} = 5.3 \times 10^{10} M_{\odot}, \quad M^{*}_{\mathrm{M\,31+sat}} = 6.0 \times 10^{10} M_{\odot}. \qquad (6)$$

Using (4) and (6) we obtained:

$$\chi_{\mathrm{MW}} = 25.5, \qquad \chi_{\mathrm{M\,31}} = 27.5 \qquad (7)$$

The obtained values of χ are significantly lower than those corresponding to the standard ΛCDM cosmological model with $\Omega_m \approx 0.28$. Indeed, the value of $M/L_K = 97 \cdot M_{\odot}/L_{K,\odot}$ with adoption $M^{\star}/L_K = 1 \cdot M_{\odot}/L_{K,\odot}$ corresponds to the value $\Omega_m \approx 0.28$ [5]. Simple proportionality gives $\Omega_m \approx 0.09$ when $\chi = 31$.

Fig. 4 shows the dependence of the logarithm of χ on the tidal index for three systems: MW (filled squares), M 31 (filled diamonds), and LG (open large diamonds). The value of the orbital and stellar mass for the Local Group is calculated using simple addition. For values Θ_{lim} of $-0.5..0.5$ the value of χ is in the range 24.7..27.8 for MW and 27.4..28.6 for M 31. For LG, the value $\chi_{\mathrm{LG}} = 26.5$ was obtained for $\Theta_{\mathrm{lim}} = 0$.

The level $\chi = 31$ ($\log \chi = 1.491$) was marked by dashed line. As can be seen, in the given range the Θ_{lim} value χ does not exceed $\chi = 31$. If $\chi = 31$ is taken as the average value in the Universe, then in the standard cosmological ΛCDM models it corresponds with the value $\Omega_m \approx 0.09$ instead of the generally accepted value $\Omega_m = 0.28$. This last value is realised only in rich clusters. Taking into account that the cluster contains only 10% of the total number of galaxies (while the rest are in groups or field galaxies), our results confirm the well-known problem of "lack of DM" in the Local group.

It is clear that the ratio of full (orbital) mass to baryonic mass is lower. Let us take into account the mass of the gas in M 31. The mass of neutral hydrogen in M 31 is $5.4 \times 10^{9} M_{\odot}$ [8]. The multiplication factor 1.85 brings this value to the total mass of gas (plus helium and molecular hydrogen) [11], which gives approximately $1 \times 10^{10} M_{\odot}$. Then, the baryon mass (stellar plus gas), is $M_B = 7.0 \times 10^{10} M_{\odot}$ and $\chi_B \equiv M_{\mathrm{orb}}/M_B \approx 24$, that is, per mass unit of baryons there are 23 mass units of DM (excluding the intergalactic medium).

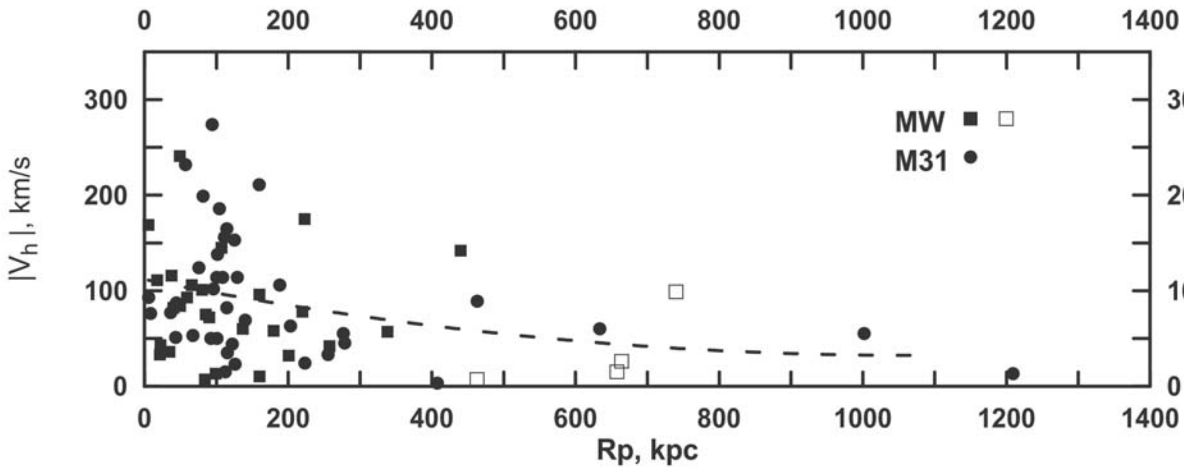

Fig. 1: The distribution of the MW and M 31 satellites in the plane (R_p) - $(|V_h|)$.

CONCLUSIONS

In the present paper the estimates of the orbital mass of the Milky Way and the Andromeda galaxy (M 31) were obtained, based on the most complete current data on the relative radial velocities and distances to their respective satellites [8]. Our estimates are in a good agreement with recent determinations using various methods [13]. The ratio of the total mass of galaxies to their stellar mass is ~ 30. If this value is taken as the average value in the Universe, then these results will agree with the standard cosmological ΛCDM models, with the value $\Omega_m \approx 0.09$ instead of the generally accepted value $\Omega_m \approx 0.28$. This last value is attained only in rich clusters. Taking into account that the cluster contains only 10% of the total number of galaxies, while the rest of are in groups or field galaxies, our results confirm the well-known problem of "lack of dark matter" in the Local group (more about this problem see [5]).

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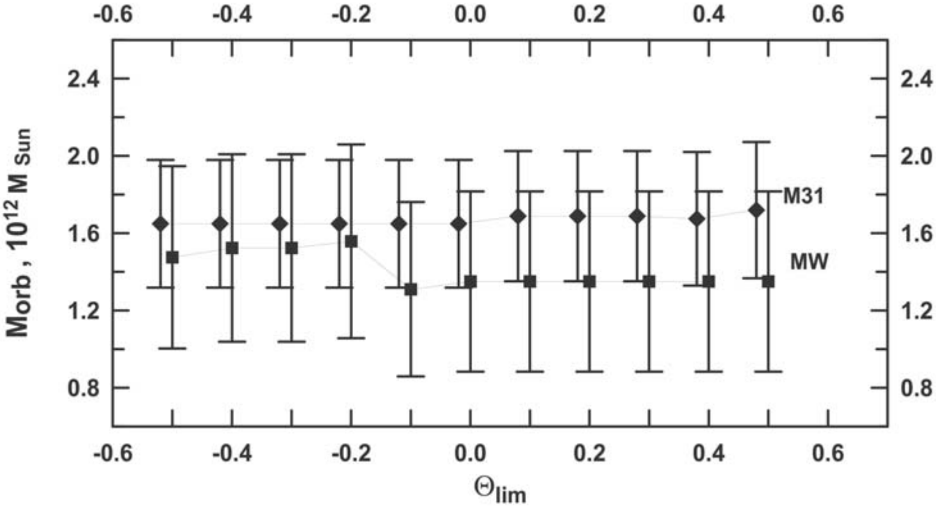

Fig. 2: The dependence on the limiting tidal index of the orbital mass of the MW and M 31

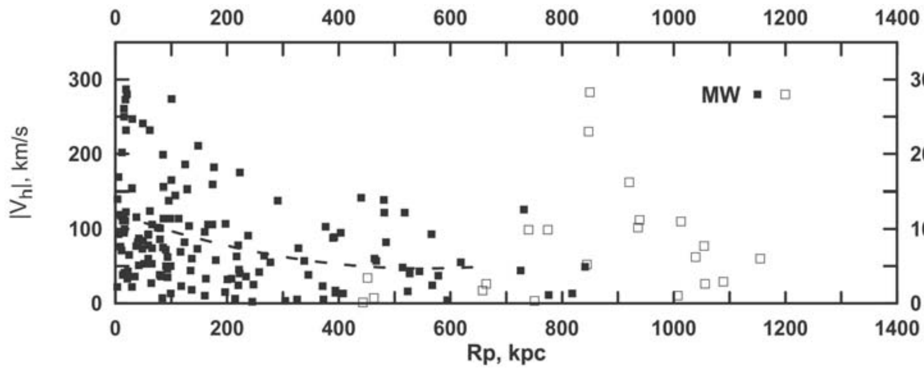

Fig. 3: The distribution of the "synthetic" MW satellites in the plane $(R_p) - (|V_h|)$.

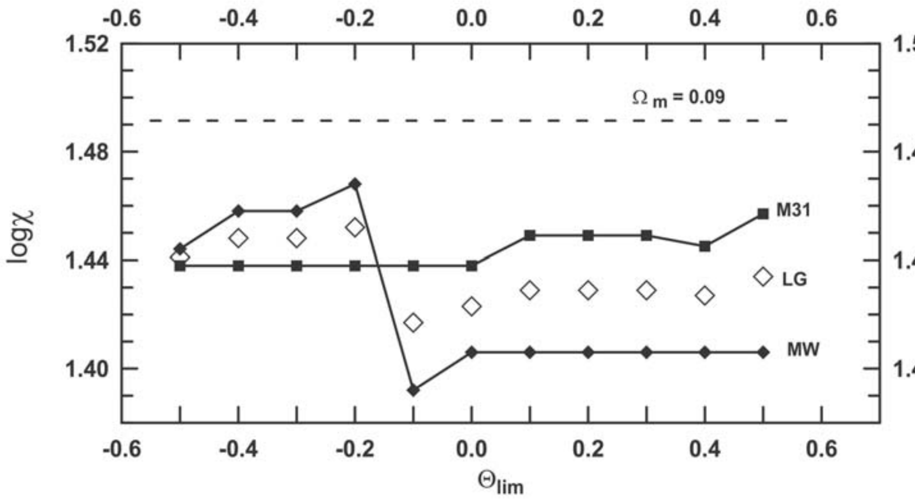

Fig. 4: The dependence of the logarithm of the ratio of the orbital mass to stellar mass for the Milky Way, M 31 and the Local Group on the limiting value of tidal index.