already recorded CMB anisotropy, the polarization of radiation will be studied for the first time at the signal detection level. However, for polarization experiments, in which the signal-to-noise ratio does not exceed a few units (unlike the anisotropy, for which the signal-to-noise ratio is expected to be 10 – 30), of extreme importance are the methods of filtration of galactic and extragalactic noises related to the polarization properties of synchrotron and free-free emission, due to the dust radiation, contribution from point sources, etc. Of special importance for the future polarization experiments is taking into account the anisotropy that is introduced by the receiving tract and depends on the reception frequency due to the apparatus features of the experiment. In this connection, methods of data processing that are capable of maximum cleaning of noise from maps (rather than 'spreading' them over the power spectrum) should play a crucial role in the signal extraction. One such method involves an amplitude – phase analysis [10] based on removing noise not in the amplitude but in the phase space, where non-gaussian noise turns out to appear most significantly. An important role in the noise identification should be played by the method of singular points of the polarization field [11 – 13], which takes into account the fact that the signal structure in the zones without original polarization ('singular points') is determined by noise. The phase analysis of anisotropy and polarization maps is especially important to distinguish the contribution from the receiving tract (antenna + aberrations). By and large, the above methods of cleaning anisotropy and polarization maps will be an invaluable addition to such traditional methods as MEM (maximum entropy method), RC (radical compression), and wavelet analysis.

To conclude, we emphasize that in the next 10 years, undoubtedly, outstanding results will be obtained in experimental studies of the CMB anisotropy and polarization, which will naturally summarize almost half a century of CMB research. Looking into the future, we can say with certainty that the epoch of MAP and PLANCK projects will bring us plenty of bright important discoveries that will advance our understanding of the general laws (and details!) of the structure and evolution of the Universe.

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Hidden mass in the Local Universe

I D Karachentsev

1. Brief history

The history of studies of hidden (dark, obscured) matter in the Universe traces back to 1933, when F Zwicky discovered [1] that masses tens of times higher than the sum of masses of individual galaxies are required to explain the observed velocities of galaxies in rich clusters. Later, the inconsistency between the 'virial' (based on the virial theorem) and individual masses was shown to be typical of galactic systems of different scales, from pairs and groups to clusters and superclusters of galaxies. In the 1970s, Freeman, Sancisi, and Rubin discovered that the rotational curves of many galaxies do not approach the Keplerian asymptotic at large distances from the centers but instead remain 'flat', which requires a substantial mass to be present at the outskirts of the galaxies [3]. Some authors believed that massive dark 'coronae' extend tens of times further than the visible boundaries of galaxies and that their total mass is capable of explaining the 'virial paradox' in clusters [4, 5]. In the 1980s, the X-ray emission of hot gas in galactic clusters with temperatures exactly corresponding to the virial motions of the galaxies was detected [6]. Finally, the most direct determinations of cluster masses from the gravitational lensing effect or shape distortions in the images of more distant galaxies [7] confirmed the presence of large unseen masses in rich clusters. It is firmly established that the estimates of rich cluster masses obtained using both virial motions and X-ray gas-emission properties and gravitational lensing effects agree within 50%.

However, such an agreement has not yet been reached on all scales of the Universe structural hierarchy. Table 1 lists the main mean characteristics of galactic systems of different scales, from single galaxies to clusters: the radius of the system, the root-mean-square velocity of the internal motions, the relative number of galaxies in the system at a given level, the total mass-to-luminosity ratio $M_\odot/L_\odot$, the mean dark-to-visible mass ratio (DM/LM), and the relative contribution of the galactic system to the total mass density in the Universe. Here the Hubble constant is taken to be $H = 70$ km s^{-1} Mpc^{-1}, which corresponds to the critical

Table 1. The dark matter distribution.

Properties	Galaxies	Pairs	Groups	Clusters
Radius, Mpc	0.03	0.09	0.25	1.7
R.m.s. velocity, km s^{-1}	(25)	35	70	600
Relative number of galaxies	0.35	0.15	0.40	0.10
in the system	20	20	30 – (200)	250
$M_\odot/L_\odot$ Method of estimation	Rotational curves	Orbital motions	Virial motions, sphere $V = 0$	X-ray, grav. lensing
	2	2	3 – (27)	35
DM/LM	15 %	6 %	27 %	52 %
Specific contribution to the total mass	(6 %)	(2 %)	(72 %)	(20 %)

density $\Omega_0 = 1.0 \times 10^{-29}$ g cm^{-3}. Within the standard optical radius, the visible-mass-to-luminosity ratio for a typical galaxy is about $7M_\odot/L_\odot$. For the mean luminosity density in the Universe $1.4 \times 10^8 L_\odot$ Mpc^{-3} [5], the mean dark matter density is about 0.048 – 0.125 in units of the critical density.

The data presented here show that the intermediate hierarchical class, groups of galaxies, has the maximum difference in the hidden-mass estimates. Many authors find the mean virial-mass-to-luminosity ratio for groups to be $\sim 200M_\odot/L_\odot$ [8]. However, our data [9] indicate this ratio to be only $\sim 30M_\odot/L_\odot$. In the first case, groups of galaxies give the main contribution (72%) to the total density in the Universe, while in the second case the main contribution (52%) is provided by rich clusters. This also causes the uncertainties in the mean dark matter density determination in the Universe (from 0.048 to $0.125\Omega_0$). To clarify the situation, a detailed systematical study of the structure and dynamics of the closest groups of galaxies was required.

2. Topography of the Local Universe

As was stressed many times by J Peebles [10], precise knowledge of the distances and velocities of nearby galaxies allows one to calculate their mutual positions at different epochs Z and thus to determine the value of Ω_m at $\sim (1-10)$ Mpc scales. Unfortunately, until recent years the situation with radial velocities and, especially, with distances to galaxies in the Local Universe was discouragingly poor. For example, in a sample of $N = 179$ neighboring galaxies with radial velocities $V < 500$ km s^{-1} [11], reliable distances had been determined only for 8% of the galaxies. Moreover, recently strong arguments were put forward that the expected galactic number density in the Universe is an order (!) of magnitude higher than the observed one [12, 13]. It is assumed that not yet discovered galaxies are dwarf systems with a very low surface brightness and their contribution to the total mass is comparable with that from normal galaxies.

In recent years, at the Special Astrophysical Observatory (SAO) of the Russian Academy of Sciences, in cooperation with the Max-Planck-Institut (Germany) and other observatories in Spain, the USA, the Ukraine, and Finland, a program of searching for and investigation of new nearby galaxies has been carried out. The program includes the following stages.

(1) Searching for new nearby dwarf galaxies on the reproductions of the photographic sky survey POSS-II and ESO/ESRC. As a result, more than 600 nearby galaxy candidates were discovered.

(2) Measuring the radial velocities of the new galaxies using 21 cm neutral hydrogen line observations, with radio telescopes of Germany, France, and Australia, as well as using optical emission lines, with the 6-m telescope of the SAO RAS.

(3) Large-scale imaging of all close galaxies on the 6-m telescope and other telescopes with CCD detectors and resolving the galaxies into stars with an accuracy of $\sim 20\%$ using the luminosity of the brightest stars.

(4) Surveying the closest 200 galaxies using the Hubble Space Telescope, measuring their distances with an accuracy of $\sim 5\%$ from the luminosities of the red giant branch stars.

The main stages of this project have now been completed. The number of galaxies in the Local Volume, bounded by a distance of $D = 7$ Mpc or by radial velocities $V < 500$ km s^{-1}, has been doubled. The number of galaxies with measured (photometric) distances has been increased by more than an order of magnitude [14 – 16]. A unique stratum of new observational data has been obtained, which has allowed for the first time the reconstruction of a three-dimensional map of the Local Volume of the Universe and to study the peculiar velocity field inside it.

The relief of the Local Universe has a pronounced fractal structure with voids of different scales. Galaxies assemble into filamentary and planar structures surrounding the voids. Of the entire population of the Local Volume (340 galaxies), more than a half are concentrated in the attraction zone only of 7 of the most massive galaxies. These galaxy 'oligarchs' include, in particulars our Milky Way. The spatial crowding of galaxies is characterized by a two-point correlation function with a standard power law $\gamma = -1.8$. The standard Peebles correlation function describes the assembling of galaxies down to a scale comparable with the diameter of an individual galaxy (30 kpc).

3. Anisotropy of the velocity field of galaxies

The new data on the radial velocities and distances of 180 galaxies from the Local Volume reveal significant deviations from the isotropic Hubble expansion [16]. The observed distribution of the local Hubble parameter over the sky can be represented by a triaxial ellipsoid with an axis ratio $H_a : H_b : H_c = 81 : 62 : 48$ km s^{-1} Mpc^{-1} to within an uncertainty of $\sim 8\%$. Minimum values of the Hubble parameter are observed along the polar axis of the Local Supercluster, and the region of maximum values lies along the Supercluster's equator, at an angle of $\Theta = 29^\circ \pm 5^\circ$ with respect to the Virgo cluster center. By and large, the local pattern of the non-Hubble motion of galaxies has little correspondence with the well-known model of a spherically symmetric flow of galaxies towards the Virgo center [17]. One of the reasons for this discrepancy could be the differential rotation of the Local Supercluster. However, the existence of the large angular momentum on a ~ 10 Mpc scale is hard to understand in the framework of the modern cosmological models.

4. The Local Group and Hubble dependence in its surroundings

Our Galaxy (Milky Way) and the Andromeda galaxy (M31) together with 30 of their satellites form the Local Group. The volume distribution of the 70 closest galaxies inside and around the Local Group in a ± 3 Mpc cube is shown in Fig. 1. For most of these galaxies, precise distance measurements have been carried out during the last two years. The two darker balls around the Andromeda galaxy indicate the two new satellites discovered at SAO in 1999 [18]. Figure 2 shows the radial velocity V_LG — distance D_LG relation for the nearest galaxies outside the Local Group. The Hubble dependence $V = HR$ relative to the Local Group centroid exhibits the expected non-linear effect due to the gravitational braking of the Hubble flow by the Local Group mass. The radius of the zero-velocity sphere R_0 and the total mass of the group are simply related as $M_\mathrm{LG} = (\pi^2/8G)H^2R_0^3$ [19], where G is the Newton gravity constant. For $H = 70$ km s^{-1} Mpc^{-1} and the observed value $R_0 = 0.96 \pm 0.05$ Mpc, the total mass of the Local Group is $(1.2 \pm 0.2) \times 10^{12} M_\odot$ and the mass-to-luminosity ratio is $M/L = (23 \pm 4)M_\odot/L_\odot$. Note that the obtained total mass agrees well with the sum of the mass of M31 $(0.8 \pm 0.4) \times 10^{12} M_\odot$ and that of the Milky Way $(0.9 \pm 0.4) \times 10^{12} M_\odot$, as estimated from the orbital motions of their satellites on the scale ~ 200 kpc [20, 21].

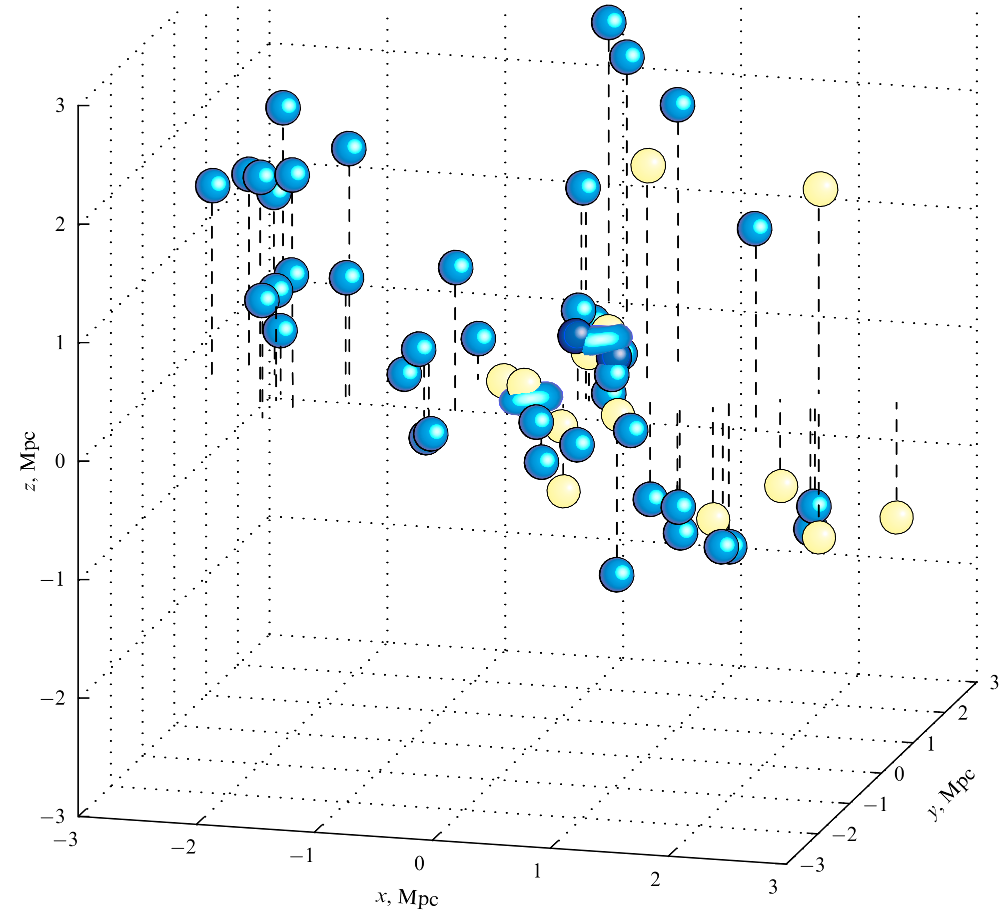

Figure 1. The Local group and ist surroundings.

Most galaxies in Fig. 2 are well-isolated objects. Their radial-velocity variance with respect to the Hubble law is only 25 km s^{-1}, which can be considered the first reliable estimate of thermal (chaotic) galactic motions in the space between groups. With due account for the virial motions, the mean radial-velocity variance in the Local Volume is 72 km s^{-1}. According to [22], such a 'cold' field of peculiar velocities limits the mean local matter density to $\Omega_m < 0.08$.

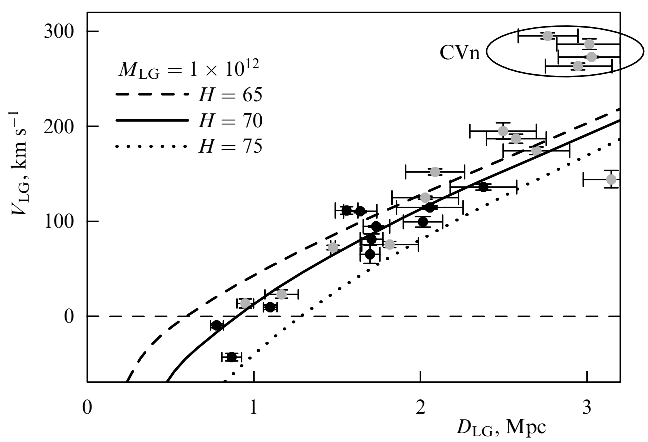

Figure 2. Velocities and distances of nearby galaxies relative to the centroid of the Local Group. The three lines (from left to right) correspond to the expected Hubble dependence for $H = 70$ km s^{-1} Mpc^{-1} and values for the total mass of the Local Group of 3×10^{11}, 1×10^{12} and $3 \times 10^{12} M_{\odot}$. The oval marks four galaxies from the 'cloud' of Canes Venatici.

5. The nearby complex of galaxies M81

The group of galaxies nearest to us includes the spirals M81, NGC2403, NGC4236 and extends in the form of a filament over $\sim 30°$. In view of the 12 recently discovered dwarf systems, the population of the complex amounts to 34 galaxies. Radial velocities have been measured for 23 of them, and distance determinations have been made for 28 of them using the Hubble Space Telescope with an accuracy of $\sim$ 200 kpc [23]. From an analysis of the volume structure and kinematics of this complex, the zero-velocity sphere radius of the M81 group was determined to be 1.1 Mpc, which corresponds to a total mass of $1.8 \times 10^{12} M_{\odot}$ or a total-mass-to-luminosity ratio of $30 M_{\odot}/L_{\odot}$. The masses of galaxies M81 ($1.4 \times 10^{12} M_{\odot}$) and NGC 2403 ($0.4 \times 10^{12} M_{\odot}$) derived from the orbital motions of their satellites are in good agreement with the total group mass estimate. Therefore, both in the case of the Local Group and the M81 group, the total group mass (a scale of $\sim$ 1 Mpc) is consistent with the sum of orbital (virial) masses of the main galaxies in the subgroups (scales of 100 – 200 kpc). This implies that the main fraction of the volume of these groups is apparently not filled with dark matter.

6. Groups in the Local Supercluster

To single out groups of galaxies, simplified criteria [8, 24] have usually been applied, which ignore individual galactic properties. This has led to the contamination of groups with spurious members and a significant overestimation of the virial masses. Using more refined clusterization conditions [9, 25] notably reduced the mass estimates. The new criterion has been applied to a sample of 6300 nearest galaxies with radial velocities < 3000 km s^{-1}, concentrated within the Local Supercluster volume. As a result, 840 groups were selected that comprise 55% of the total number of galaxies in the volume. The typical characteristics of these groups are listed in Table 1. The mean crossing time of the groups does not exceed 10% of the Hubble time $1/H$. The mean virial-mass-to-luminosity ratio weakly depends on the group size and is $\sim 30 M_{\odot}/L_{\odot}$. The last value is consistent with the above total mass estimates for the Local Group and M81 group, which makes our system a typical representative of galactic groups.

7. Conclusion

A great number of possible candidates have been put forward to explain the nature of dark matter. They include: dwarf stars, black holes, molecular gas clouds, neutrinos, axions, gravitinos, etc.; see [26, 27] for reviews of various hypotheses and their observational tests. As can be seen from the last two rows of Table 1, the dark-to-visible mass ratio for single galaxies, pairs, and groups is DM/LM = 2 – 3, and only in rich clusters — dense 'knots' of the large-scale structure — this ratio increases by more than an order of magnitude. The total contribution of galaxies, pairs, and groups to the integral matter density (15% + 6% + 27%) is approximately the same as that of rich clusters (52%). Possibly, we are observing two types of dark matter that have essentially different spatial distributions: compact, dark shells of individual galaxies and vast reservoirs filling the volumes of rich clusters.

It should be stressed here that there exist a strict relation between the luminosity of a galaxy and the amplitude of its internal motions (Tully – Fisher relation for spirals, Faber – Jackson relation for E and S0 galaxies), with a dispersion of only 15 – 20%. This means that unseen masses of galaxies are 'sewed' to their visible masses in a surprisingly stable proportion spanning a luminosity range of more than three orders of magnitude.

In recent years observational evidence has emerged [28] favoring the cosmological significance of vacuum, which appears as a universal repulsion force (the famous λ term in the Einstein equation). It cannot be ruled out that, in terms of vacuum cosmology, the problem of dark matter in the Universe will look essentially different.

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Searches for black holes: the recent data

A M Cherepashchuk

Black holes are predicted by Einstein's General Relativity (GR) theory. A black hole (BH) represents a space – time region for which the parabolic velocity is equal to the speed of light $c = 300\,000$ km s^{-1}. The characteristic size of a BH is determined by the gravitational radius $r_g = 2GM/c^2$. It amounts to $r_g = 30$ km for $M = 10\,M_{\odot}$ and 20 a.u. for $M = 10^9\,M_{\odot}$. The BH event-horizon radius is $r_h = r_g$ for a non-rotating (Schwarzschild) BH and $r_h < r_g$ for a rotating one. For a BH that formed in our epoch, the event horizon has not yet formed, so these are collapsing objects ('virtual' BHs).

From the astronomical point of view, in order for an object to be recognized as a BH, its mass should be measured and its size should not exceed r_g. Also, it is necessary to obtain observational evidence for the object having a 'virtual' event horizon. BH masses are reliably measured by the surrounding gas and star motions. Since $r \gg r_g$, in most cases using the Newtonian gravity law is sufficient.

BH radii are very difficult to measure. So far only very rough ($r < 10 r_g$) indirect estimates have been used: study of the X-ray luminosity due to accretion of matter onto a BH, fast time variability analysis, spectral line profile investigations, etc. No sufficient observational criteria for a BH have been found as yet, but all the necessary conditions are met.

There are 3 known types of BHs:

(1) Stellar mass BHs with $M = 3 - 50\,M_{\odot}$. The stellar evolution ends in the formation of a white dwarf (if the stellar core mass $M_c \leqslant 1.2\,M_{\odot}$), a neutron star (NS) (if $M_c < 3\,M_{\odot}$), or a BH (if $M_c \geqslant 3\,M_{\odot}$).

(2) Supermassive BHs in galactic nuclei ($M = 10^6 - 10^{10}\,M_{\odot}$).

(3) Primordial BHs generated at the early stages of evolution of the Universe. As yet, very little is known about them from the observational point of view.

The existence of intermediate-mass BHs with $M = 10^2 - 10^4\,M_{\odot}$ located in the near-nuclear regions of galaxies (at a mean distance of ~ 390 pc from the nucleus) has been widely discussed in recent years.

Observational studies of BHs proceed in two directions:

(1) Searching for massive compact objects – BH candidates. Here much progress has been made, and the number of them approaches 100.

(2) Looking for sufficient criteria for the BH candidates discovered to be real BHs. Many difficulties have been met on this avenue, but there is some progress and great hopes for future space X-ray, interferometric, and gravitational wave experiments.