Dark Matter in the Universe: 60 Years Later

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1 Introduction

The traditional character of cosmology has been changed by the discoveries of dark matter in the Universe and of the filamentary structure of the Universe with enormous empty regions devoid of any kind of visible matter between filaments. In this year we celebrate the 60 anniversary of the discovery of the dark matter. I devote this review to some aspects of the dark matter problem.

The term dark matter is used here for any form of matter whose existence can be detected only through its gravitational effects. The presence of dark matter, its quantity and extent can be determined from the difference between the dynamical mass estimates in stellar systems and the directly counted masses of visible objects in them. If a difference between dynamical masses and directly counted masses is detected we can speak on the mass paradox or on the “missing mass”.

Mass determinations in small astronomical systems as the solar system, binary stars and small stellar systems show good mutual consistency between results obtained by different methods and there is no room left for dark matter.

A mass paradox is found in galactic disks, around galaxies, in groups, clusters and superclusters of galaxies. The mass paradox is solved by assuming the existence of dark matter in respective systems. Dark matter exists probably also in large voids between superclusters. Dynamically dark matter is dominant on all scales larger than the scale-length of ordina-
ry galactic populations. Thus the formation of galaxies and the structure of the Universe is essentially determined by the properties of dark matter. This makes the problem of the amount and nature of dark matter to the central one in the whole cosmology.

In this review I consider first shortly the methods of mass determinations in various stellar systems. Then a short history of the study of the dark matter is given. Current topical problems of the dark matter are considered next: What is the amount of matter associated with galaxies? How much matter can be located in voids? What is the mean density of matter in the Universe? What is the nature of dark matter?

2 Mass Determinations of Stellar Systems

All astronomical mass determinations are based on measurements of relative velocities, \( V \), and relative distances, \( R \), of members of a system, using the condition of gravitational equilibrium

\[
V^2 = \beta GM(R)/R
\]

where \( M(R) \) is the mass inside the orbit of test particles of radius \( R \), \( G \) is the gravitational constant, and \( \beta \) is a dimensionless constant of the order of unity, depending on the form and orientation of mutual orbits and the mass distribution.

If test particles move in nearly circular orbits, as planets around the Sun, then the velocity \( V \) is equal to the circular velocity and \( \beta = 1 \). In the solar system practically the whole mass is located in the Sun, and very little is added by planets. In this case \( M(R) = M \) and we have for the circular velocity the Kepler law

\[
V^2 = \frac{GM}{R}.
\]

This law is valid in any case when the whole mass is inside orbits of test bodies. All test particles measure the same mass and, if particles are located at different distances from the central body, we have a number of independent mass determinations, as in the case of the Solar system using the motion of different planets to derive the mass of the Sun.

Dark Matter in the Universe: 60 Years Later

If velocities and orbital planes of test particles are distributed randomly, then we have another simple case. From measurements of Doppler shifts we can determine the velocity dispersion in one coordinate, \( \sigma_r \), directed towards the observer. Now instead of the velocity, \( V \), we have the radial velocity dispersion, \( \sigma \), in this case \( \beta = 1/3 \), and we get

\[
\sigma^2 = \frac{1}{3}\frac{GM(R)}{R}.
\]

This case can be applied for spherical clusters of stars or galaxies. Using the associated luminosity obtained by photometry one can deduce the mass-to-luminosity ratio, \( M/L \), which characterizes the physical nature of the system. The velocities can be measured directly from redshifts, but the effective size, \( R \), and the total luminosity, \( L \), depend on the distance, \( D \), which is inversely proportional to the Hubble constant: \( D \propto H^{-1} \). It is convenient to express the Hubble constant in dimensionless units: \( h = H/100 \), where \( H \) is given in km/s/Mpc. Observational estimates of the Hubble constant lie in the interval \( 0.5 < h < 1 \). We have \( R \propto h^{-1} \), \( M \propto h^{-1} \), \( L \propto h^{-2} \), and \( M/L \propto h \). Masses, luminosities and \( M/L \) are usually measured in solar units.

In cosmology it is customary to calculate the quantity \( \Omega = 8\pi G\bar{\rho}/(3H^2) \), the mean mass density, \( \bar{\rho} \), measured in units of the critical closure density. This quantity is independent of the Hubble constant, since the critical as well as the mean mass density are proportional to \( h^2 \).

The masses of systems of galaxies can be determined also in an indirect way, by counting the number of their subsystems and by calculating the total mass by adding the masses of these subsystems. As noted in the Introduction, when these two different mass determinations contradict each other then we have a mass paradox or the "missing mass" problem in the system.

3 First Evidence on the Missing Mass

Historically the first attempt to estimate the density of dark matter from the difference between the dynamical mass and directly counted mass was made by Ernst Öpik (1915). In this study Öpik tried to estimate the density of dark absorbing matter in the Milky Way. Later a similar question
was asked by Oort (1932). New determinations were made by Hill (1960) and Oort (1960). They noticed that the dynamical density of mass in the galactic disk exceeds the density of directly observed matter, the discrepancy was only by two times. This invisible component must form a disk, otherwise it distorts the whole rotation curve of the Galaxy. Presently the problem of the presence of such “local dark matter” is not finally solved: observational determinations are rather uncertain, and the discussion, whether there exists local dark matter in the Galaxy or not, continue.

The actual discovery of the “missing mass” concerns clusters of galaxies: Zwicky (1933), basing on a virial analysis of 7 galaxies in the Coma cluster, argued for a discrepancy by a factor of ~ 400 between the virial $M/L$ in Coma and that of nearby galaxies. This was an overestimate because it was based on a wrong value of the Hubble constant, $H = 500$ km/s/Mpc. According to modern data the mass-to-luminosity ratio in Coma is by a factor of $\approx 100$ larger than in typical galaxies. This measures the amount of the “missing mass” in clusters of galaxies.

A similar discrepancy has been discovered in groups of galaxies. Kahn and Woltjer (1959) noticed that the mass of the Local Group of galaxies, as determined from the motion of our Galaxy in respect to the Andromeda galaxy, is of the order of $10^{12}$ $M_{\odot}$ whereas the masses of both galaxies are of the order of $10^{11}$ $M_{\odot}$. We see a discrepancy of the order of ten.

The next stage of the dark matter story was connected with individual galaxies. The mass distribution in galaxies can be determined directly from their rotation curves and indirectly from the light distribution in visible populations using photometric data. In late 60s both data were available for a few nearby galaxies and a comparison of photometric and dynamical models was possible. This comparison demonstrated the presence of mass paradox in spiral galaxies. Einasto (1969, 1972), Sizikov (1969), Freeman (1970), Rubin and Ford (1970), Rogstad and Shostak (1972) independently indicated that from photometric data one should expect a Keplerian falloff of the circular velocity on the periphery of spiral galaxies, whereas dynamical data indicate only a marginal if any decrease of the rotation velocity.

It is surprising that neither the Zwicky’s discovery nor the Kahn and Woltjer’s paper and accumulating evidence on the presence of the mass paradox in galaxies have been given attention they deserved. A real break-through in the dark matter problem came when Tartu and Princeton groups demonstrated that dark coronas or haloes around giant galaxies have an extent of several hundred kiloparsecs and total masses of galaxies exceed conventional masses tenfold (Einasto, Kaasik Saar 1974, Ostriker, Peebles, Yahil 1974). This discrepancy can be explained by the presence of a massive invisible corona around the galaxy. These results were confirmed by a systematic survey of rotation curves of galaxies by Rubin et al. (1980, 1982). Reviews of the dark matter problem in various systems of galaxies are written by Faber and Gallagher (1979) and Trimble (1987).

There may exist a general smoothly distributed dark matter background too. Studies of the large-scale structure of the Universe demonstrate that galaxies and clusters of galaxies are located in filaments which form a connected 3-dimensional network (a review is given by Oort 1983). The space between filaments is void of any visible matter. Galaxy systems fill only a few per cent of the total volume of the space (Einasto, Jõeveer, Saar 80) and diameter of voids reach tens megaparsecs (Jõeveer, Einasto, Tago 1978, Kirshner et al. 1981). A complete evacuation of voids of such large diameter is impossible since at the epoch of recombination the density distribution was still almost homogeneous, and gravitation, the only force which can evacuate voids, works slowly. We come to the conclusion that some dark matter should exist in voids.

Summarizing the dynamical evidence we can say that there are actually three dark matter problems: (1) dark matter in galactic disks; (2) dark matter associated with galaxies and clusters of galaxies; (3) a smoothly distributed background of dark matter.

### 4 Mean Density of Matter Associated with Galaxies

Most galaxies are located in systems: groups, clouds and clusters. These systems are distributed along some sort of connected network which leaves most of the Universe empty.

Gramann (1990) estimated the density of matter associated with systems of galaxies. At present, no detailed dynamical information on all galaxy systems in a large volume is available. However, in a large region we can estimate the mean luminosity density.
The mean density of matter associated with systems of galaxies in the given volume \( V \) is determined as

\[
\varrho_M = \varrho_L \sum_i \left( \frac{M_i}{L_i} \right) f_i. \tag{4}
\]

Here \( (M/L)_i \) and \( f_i \) are the mass-to-luminosity ratio and frequency of systems of different types \( i \), respectively, and \( \varrho_L \) is the mean luminosity density in the given volume.

Available estimates of the luminosity density by Jõeveer et al. (1978), Davis and Huchra (1982), Efstathiou et al. (1988) yield a mean value about \( \varrho_L \approx 1.5 \cdot 10^8 h \text{Mpc}^{-3} \). Luminosity density is given in the Zwicky B(0) system.

Adopting the value given above as the characteristic mean luminosity density in the region containing one or two superclusters, the clustered matter density parameter \( \Omega_c \) is

\[
\Omega_c = \frac{8\pi G}{3 H^2} = (6 \pm 2) \cdot 10^{-4} \sum_i \left( \frac{M_i}{L_i} \right) f_i h^{-1}. \tag{5}
\]

The mass-to-luminosity ratio \( M/L \) is expressed in solar units \( (M/L)_\odot \).

We can distinguish three types of systems: rich clusters, groups, and field galaxies. The median mass-to-luminosity ratio for rich clusters has been estimated as \( M/L \approx 500 \pm 100 h \) by Geller (1988). Mean masses and mass-to-luminosity ratios of groups of galaxies can be determined using published catalogues of groups (Geller and Huchra 1983, Vennik 1984, Tully 1987). Such determinations have been performed by several authors (Huchra and Geller 1982, Vennik 1986), and yield a mean \( M/L = 190 h \).

In the case of field galaxies we can use rotation curves. As demonstrated by Rubin et al. (1985), isolated galaxies also have flat rotation curves and thus are surrounded by dark coronas. Conservative extrapolation of mass functions \( M(R) \) yields a mass-to-luminosity ratio of the order of \( 100 h \).

From a full galaxy catalogue used in a group and cluster search, about 80\% of galaxies belong to groups, and about 5\% belong to clusters, the rest are relatively isolated galaxies. Using these data we can adopt the following frequencies for clusters, groups and field galaxies: 0.05; 0.80; 0.15. If we adopt the mean mass-to-light ratios cited above, we get for the mean mass-to-light ratio \( M/L = 190 h \) and \( \Omega_c = 0.11 \).

The main contribution to \( \Omega_c \) comes from groups. If a group is bound, but not in virial equilibrium, the application of the virial theorem for the estimate of its mass is not correct. The true median \( M/L \) of groups may be greater than the virial estimates. In this case \( \Omega_c \) increases (Giuricin et al. 1988).

If we take into account the uncertainty in both the mean luminosity density and the mass-to-luminosity ratio, and possible systematic error in \( M/L \) of groups, we get an estimate \( \Omega_c = 0.15 \pm 0.05 \).

5 Mean Density of Matter in Voids and in the Universe

The mass budget of the Universe has three basic constituents: the luminous matter (galaxies, intergalactic gas); clustered matter associated with galaxies and systems of galaxies; and non-clustered matter in voids.

Mass-to-luminosity ratios of luminous galactic populations are in the range \( 1-10 \), and we can adopt a median value 3. If we add to this amount the intergalactic gas we get the total mean density of the luminous matter, \( \Omega_{\text{lum}} \approx 0.01 \).

The clustered matter, associated with galaxies and systems of galaxies gives, has, according to data discussed in previous Section, a contribution \( \Omega_c \approx 0.15 \). This contribution is divided into two parts, given by luminous and dark matter, in a ratio 1 to 15.

Voids and superclusters are made of initial negative and positive density fluctuations, respectively. In a random Gaussian fluctuation field positive and negative fluctuations are interchangeable; thus the amount of matter in both types of fluctuations is initially equal. During the subsequent evolution matter flows from low-density regions toward high-density regions. The rate of flow of matter from low density regions can be found numerically.

Numerical simulations by Einasto et al. (1994) show that the fraction of particles in low-density regions (voids) is presently \( F_v \approx 0.15 \), respectively the total amount of matter in voids in units of the critical density \( \Omega_c \approx 0.03 \). The density value is fairly robust, for a wide range of models results are almost identical.
The total amount of matter in the Universe, including both clustered and non-clustered matter, is $\Omega_0 = \Omega_c + \Omega_v \approx 0.2$.

The favored value from the inflation theory is $\Omega = 1$. A low density universe satisfies this constraint if a cosmological constant is used

$$\Omega_0 + \Omega_A = \Omega. \quad (6)$$

If we adopt data quoted above, we get $\Omega_A = 0.8$.

The total density of matter $\Omega_0$ can be determined also directly. Observational estimates are, however, rather uncertain, and give discordant results. Values from 0.3 to 1.0 have been obtained, the results being model-dependent.

To summarize we can say that the available observations have not yet fixed a reliable mean density value.

6 Nature of Dark Matter

The local dark matter (if it exists) is without any doubt baryonic. Its contribution to the total mass budget of the Universe is rather small.

Nucleosynthesis studies suggest that the total density of baryonic matter must be $\Omega_{\text{bar}} \approx 0.05 - 0.1$. This estimate is not very different from the presently estimated total amount of matter, $\Omega_0 \approx 0.2$. Thus dark matter in coronas of galaxies and clusters may consist of some non-dissipative form of baryonic objects. The real problem here is how to transfer ordinary primeval gas in a very early stage and with high efficiency to the dark form and then stop the process abruptly to explain the gap between the physical and dynamical properties of dark matter and ordinary stellar populations.

The dark matter may as well be non-baryonic, except that massive neutrinos (hot dark matter) cannot be confined to small coronas around galaxies because of phase-space density constraints (Tremaine and Gunn 1979). Thus non-baryonic dark coronas of galaxies must be made of some sort of cold dark matter which can form small coronas too.

Dark matter in voids must be of the same type as in the clustered component around galaxies due to the continuous exchange of matter between voids and galaxy systems. A certain fraction of it can be baryonic. This fraction must be identical in the clustered and non-clustered component.

References