DARK MATTER

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Contents

Summary

The dark matter story passed through several stages on its way from a minor observational puzzle to a major challenge for theory of elementary particles.

I begin the review with the description of the discovery of the mass paradox in our Galaxy and in clusters of galaxies. First hints of the problem appeared already in 1930s and later more observational arguments were brought up, but the issue of the mass

paradox was mostly ignored by the astronomical community as a whole. In mid 1970s the amount of observational data was sufficient to suggest the presence of a massive and invisible population around galaxies and in clusters of galaxies. The nature of the dark population was not clear at that time, but the hypotheses of stellar as well as of gaseous nature of the new population had serious difficulties. These difficulties disappeared when non-baryonic nature of dark matter was suggested in early 1980s.

The final break through came in recent years. The systematic progress in the studies of the structure of the galaxies, the studies of the large scale structure based on galaxy surveys, the analysis of the structure formation after Big Bang, the chemical evolution of the Universe including the primordial nucleosynthesis, as well as observations of the microwave background showed practically beyond any doubt that the Universe actually contains more dark matter than baryonic matter! In addition to the presence of Dark Matter, recent observations suggest the presence of Dark Energy, which together with Dark Matter and ordinary baryonic matter makes the total matter/energy density of the Universe equal to the critical cosmological density. Both Dark Matter and Dark Energy are the greatest challenges for modern physics since their nature is unknown.

There are various hypotheses as for the nature of the dark matter particles, and generally some form of weakly interactive massive particles (WIMPs) are strongly favored. These particles would form a relatively cold medium thus named Cold Dark Matter (CDM). The realization that we do not know the nature of basic constituents of the Universe is a scientific revolution difficult to comprehend, and the plan to hunt for the dark matter particles is one of the most fascinating challenges for the future.

1. Dark Matter Problem as a Scientific Revolution

Almost all information on celestial bodies comes to us via photons. Most objects are observed because they emit light. In other cases, like for example in some nebulae, we notice dark regions against otherwise luminous background which are due to absorption of light. Thus both light absorption and light emission allow to trace the matter in the Universe, and the study goes nowadays well beyond the optical light. Modern instruments have first detected photon emission from astronomical bodies in the radio and infrared regions of the spectrum, and later also in the X-ray and gamma-ray band, with the use of detectors installed in space.

Presently available data indicate that astronomical bodies of different nature emit (or absorb) photons in very different ways, and with very different efficiency. At the one end there are extremely luminous supernovae, when a single star emits more energy than all other stars of the galaxy it belongs to, taken together. At the other extreme there are planetary bodies with a very low light emission per mass unit. The effectiveness of the emissivity can be conveniently described by the mass-to-light ratio of the object, usually expressed in Solar units in a fixed photometric system, say in blue (B) light. The examples above show that the mass-to-light ratio M/L varies in very broad range. Thus a natural question arises: Do all astronomical bodies emit or absorb light? Observations carried out in the past century have led us to the conclusion that the answer is probably NO.

Astronomers frequently determine the mass by studying the object emission. However, the masses of astronomical bodies can be also determined directly, using motions of other bodies (considered as test particles) around or within the body under study. In many cases such direct total mass estimates exceed the estimated luminous masses of known astronomical bodies by a large fraction. It is customary to call the hypothetical matter, responsible for such mass discrepancy, **Dark Matter**.

The realization that the presence of dark matter is a serious problem which faces both modern astronomy and physics grew slowly but steadily. Early hints did not call much attention.

The first indication for the possible presence of dark matter came from the dynamical study of our Galaxy. Dutch astronomer Jan Henrik Oort analyzed in 1932 vertical motions of stars near the plane of the Galaxy and calculated from these data the vertical acceleration of matter. He also calculated the vertical acceleration due to all known stars near the Galactic plane. His result was alarming: the density due to known stars is not sufficient to explain vertical motions of stars – there must be some unseen matter near the Galactic plane.
The second observation was made by Fritz Zwicky in 1933. He measured radial velocities of galaxies in the Coma cluster of galaxies, and calculated the mean random velocities in respect to the mean velocity of the cluster. Galaxies move in clusters along their orbits; the orbital velocities are balanced by the total gravity of the cluster, similar to the orbital velocities of planets moving around the Sun in its gravitation field. To his surprise Zwicky found that orbital velocities are almost a factor of ten larger than expected from the summed mass of all galaxies belonging to the cluster. Zwicky concluded that, in order to hold galaxies together in the cluster, the cluster must contain huge amounts of some Dark (invisible) matter.

The next hint of the dark matter existence came from cosmology.

One of the cornerstones of the modern cosmology is the concept of an expanding Universe. From the expansion speed it is possible to calculate the critical density of the Universe. If the mean density is less than the critical one, then the expansion continues forever; if the mean density is larger than the critical, then after some time the expansion stops and thereafter the Universe starts to collapse. The mean density of the Universe can be estimated using masses of galaxies and of the gas between galaxies. These estimates show that the mean density of luminous matter (mostly stars in galaxies and interstellar or intergalactic gas) is a few per cent of the critical density. This estimate is consistent with the constraints from the primordial nucleosynthesis of the light elements.

Another cornerstone of the classical cosmological model is the smooth distribution of galaxies in space. There exist clusters of galaxies, but they contain only about one tenth of all galaxies. Most of the galaxies are more or less randomly distributed and are called field galaxies. This conclusion is based on counts of galaxies at various magnitudes and on the distribution of galaxies in the sky.

Almost all astronomical data fitted well to these classical cosmological paradigms until

1970s. Then two important analyses were made which did not match the classical picture. In mid 1970s first redshift data covering all bright galaxies were available. These data demonstrated that galaxies are not distributed randomly as suggested by earlier data, but form chains or filaments, and that the space between filaments is practically devoid of galaxies. Voids have diameters up to several tens of megaparsecs.

At this time it was already clear that structures in the Universe form by gravitational clustering started from initially small fluctuations of the density of matter. Matter "falls" to places where the density is above the average, and "flows away" from regions where the density is below the average. This gravitational clustering is a very slow process. In order to form presently observed structures, the amplitude of density fluctuations must be at least one thousandth of the density itself at the time of recombination, when the Universe started to be transparent. The emission coming from this epoch was first detected in 1965 as a uniform cosmic microwave background. When finally the fluctuations of this background were measured by COBE satellite they appeared to be two orders of magnitude lower than expected from the density evolution of the luminous mass.

The solution of the problem was suggested independently by several theorists. In early 1980s the presence of dark matter was confirmed by many independent sources: the dynamics of the galaxies and stars in the galaxies, the mass determinations based on gravitational lensing, and X-ray studies of clusters of galaxies. If we suppose that the dominating population of the Universe – Dark Matter – is not made of ordinary matter but of some sort of non-baryonic matter, then density fluctuations can start to grow much earlier, and have at the time of recombination the amplitudes needed to form structures. The interaction of non-baryonic matter with radiation is much weaker than that of ordinary matter, and radiation pressure does not slow the early growth of fluctuations.

The first suggestions for the non-baryonic matter were particles well known at that time to physicists – neutrinos. However, this scenario soon led to major problems. Neutrinos move with very high velocities which prevents the formation of small structures as galaxies. Thus some other hypothetical non-baryonic particles were suggested, such as axions. The essential property of these particles is that they have much lower velocities. Because of this the new version of Dark Matter was called Cold, in contrast to neutrino-dominated Hot Dark Matter. Numerical simulations of the evolution of the structure of the Universe confirmed the formation of filamentary superclusters and voids in the Cold Dark Matter dominated Universe.

The suggestion of the Cold Dark Matter has solved most problems of the new cosmological paradigm. The actual nature of the CDM particles is still unknown. Physicists have attempted to discover particles which have properties needed to explain the structure of the Universe, but so far without success.

One unsolved problem remained. Estimates of the matter density (ordinary + dark matter) yield values of about 0.3 of the critical density. This value – not far from unity but definitely smaller than unity – is neither favored by theorists nor by the data, including the measurements of the microwave background, the galaxy dynamics and the expansion rate of the Universe obtained from the study of supernovae. To fill the matter/energy density gap between unity and the observed matter density it was assumed that some sort of vacuum energy exists. This assumption is not new: already Einstein added to his cosmological equations a term called the Lambda-term. About ten years ago first direct evidence was found for the existence of the vacuum energy, presently called Dark Energy. This discovery has filled the last gap in the modern cosmological paradigm.

In the International Astronomical Union (IAU) symposium on Dark Matter in 1985 in Princeton, Scott Tremaine characterized the discovery of the dark matter as a typical scientific revolution, connected with changes of paradigms. Kuhn (1970) in his book *The Structure of Scientific Revolutions* discussed in detail the character of scientific revolutions and paradigm changes. There are not so many areas in modern astronomy where the development of ideas can be described in these terms, thus we shall discuss the Dark Matter problem also from this point of view.

2. Early Evidence of the Existence of Dark Matter

2.1 Local Dark Matter

The dynamical density of matter in the Solar vicinity can be estimated using vertical oscillations of stars around the galactic plane. The orbital motions of stars around the galactic center play a much smaller role in determining the local density. Ernst Öpik (1915) found that the summed contribution of all known stellar populations (and interstellar gas) is sufficient to explain the vertical oscillations of stars – in other words, there is no need to assume the existence of a dark population. A similar analysis was made by Jacobus C. Kapteyn (1922), who first used the term “Dark Matter” to denote invisible matter which existence is suggested by its gravity only. Both Öpik and Kapteyn found that the amount of invisible matter in the Solar neighborhood is small.

Another conclusion was obtained by Jan Oort (1932). His analysis indicated that the total density, found from dynamical data, exceeds the density of visible stellar populations by a factor of up to 2. This limit is often called the Oort limit. This result means that the amount of invisible matter in the Solar vicinity should be approximately equal to the amount of visible matter.

The local density of matter has been re-determined by various authors many times. Grigori Kuzmin (1952, 1955) and his students Heino Eelsalu and Mihkel Jõeveer confirmed the earlier result by Öpik. A number of other astronomers, including more recently John Bahcall, found results in agreement with Oort's result. This discussion was open until recently; we will describe the present conclusions below.

For long time no distinction between local and global dark matter was made. The realization, that these two types of dark matter have very different properties and nature came from the detailed study of galactic models, as we shall discuss below (Einasto 1974).

2.2 Global Dark Matter – Clusters, Groups and Galaxies

A different mass discrepancy was found by Fritz Zwicky (1933). He measured redshifts of galaxies in the Coma cluster and found that the velocities of individual galaxies with respect to the cluster mean velocity are much larger than those expected from the estimated total mass of the cluster, calculated from masses of individual galaxies. The only way to hold the cluster from rapid expansion is to assume that the cluster contains huge quantities of some invisible dark matter. According to his estimate the amount of dark matter in this cluster exceeds the total mass of cluster galaxies at least tenfold, probably even more. As characteristic in scientific revolutions, early indications of problems in current paradigms are ignored by the community, this happened also with the Zwicky's discovery.

The stability of clusters of galaxies was discussed in a special meeting during the IAU General Assembly in 1961. Here the hypothesis of Ambartsumian on the expansion of clusters was discussed in detail. Van den Bergh drew attention to the fact that the dominating population in elliptical galaxies is the bulge consisting of old stars, indicating that cluster galaxies are old. It is very difficult to imagine how old cluster galaxies could form an instable and expanding system. These remarks did not find attention and the problem of the age and stability of clusters remained open.

The next step in the study of masses of systems of galaxies was made by Kahn and Woltjer (1959). They paid attention to the fact that most galaxies have positive redshifts as a result of the expansion of the Universe; only the Andromeda galaxy (M31) has a negative redshift of about 120 km/s, directed toward our Galaxy. This fact can be explained, if both galaxies, M31 and our Galaxy, form a physical system. A negative radial velocity indicates that these galaxies have already passed the apogalacticon of their relative orbit and are presently approaching each other. From the approaching velocity, the mutual distance, and the time since passing the perigalacticon (taken equal to the present age of the Universe), the authors calculated the total mass of the double system. They found that $M_{\rm tot} \geq 1.8 \times 10^{12}\ M_{\odot}$. The conventional masses of the Galaxy and M31 are of the order of $2 \times 10^{11}\ M_{\odot}$. In other words, the authors found evidence for the presence of additional mass in the Local Group of galaxies. The authors suggested that the extra mass is probably in the form of hot gas of temperature about 5×10^5 K. Using more modern data Einasto & Lynden-Bell (1982) made a new estimate of the total mass of the Local Group, using the same approach, and found the total mass of $4.5 \pm 0.5 \times 10^{12} M_{\odot}$. This estimate is in good agreement with new determinations of the sum of masses of M31 and the Galaxy including their dark halos (see below).

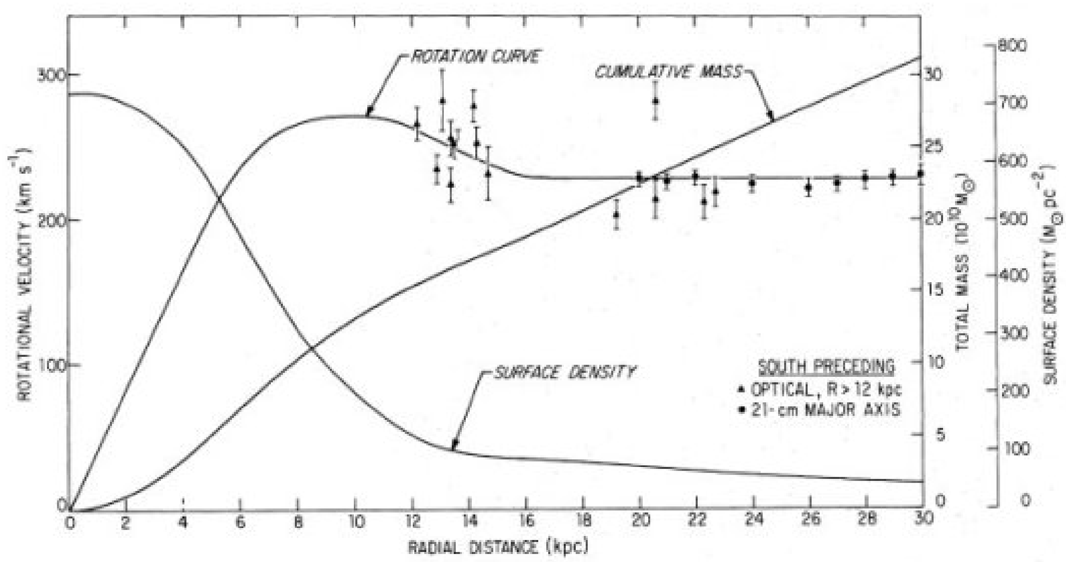

Figure 1. The rotation curve of M31 by Roberts (1975). The filled triangles show the optical data from Rubin and Ford (1970), the filled circles show the 21-cm measurements made with the 300-ft radio telescope (reproduced by permission of the AAS and the author).

A certain discrepancy was also detected between masses of individual galaxies and masses of pairs and groups of galaxies. The conventional approach for the mass determination of pairs and groups of galaxies is statistical. The method is based on the virial theorem and is almost identical to the procedure used to calculate masses of clusters of galaxies. Instead of a single pair or group often a synthetic group is used consisting of a number of individual pairs or groups. These determinations yield for the mass-to-light ratio (in blue light) the values $M/L_{\mathrm{B}} = 1\ldots20$ for spiral galaxy dominated pairs, and $M/L_{\mathrm{B}} = 5\ldots90$ for elliptical galaxy dominated pairs (for a review see Faber & Gallagher 1979). These ratios are larger than found from local mass indicators of galaxies (velocity dispersions at the center and rotation curves of spiral galaxies). However, it was not clear how serious is the discrepancy between the masses found using global or local mass indicators.

2.3 Rotation Curves of Galaxies

Another problem with the distribution of mass and mass-to-light ratio was detected in spiral galaxies. Babcock (1939) obtained spectra of the Andromeda galaxy M31, and found that in the outer regions the galaxy is rotating with an unexpectedly high velocity, far above the expected Keplerian velocity. He interpreted this result either as a high mass-to-light ratio in the periphery or as a strong dust absorption. Oort (1940) studied the rotation and surface brightness of the edge-on S0 galaxy NGC 3115, and found in the outer regions a mass-to-light ratio ~ 250. Subsequently, Rubin & Ford and Roberts & Rots extended the rotation curve of M31 up to a distance ~ 30 kpc, using optical and radio data, respectively. The rotation speed rises slowly with increasing distance from the center of the galaxy and remains almost constant over radial distances of 16–30 kpc, see Figure 1.

The rotation data allow us to determine the distribution of mass, and the photometric data – the distribution of light. Comparing both distributions one can calculate the local value of the mass-to-light ratio. In the periphery of M31 and other galaxies studied the local value of M/L, calculated from the rotation and photometric data, increases very rapidly outwards, if the mass distribution is calculated directly from the rotation velocity. In the periphery old metal-poor halo-type stellar populations dominate. These metal-poor populations have a low $M/L \approx 1$ (this value can be checked directly in globular clusters which contain similar old metal-poor stars as the halo). In the peripheral region the luminosity of a galaxy drops rather rapidly, thus the expected circular velocity should decrease according to the Keplerian law. In contrast, in the periphery the rotation speeds of galaxies are almost constant, which leads to very high local values of $M/L > 200$ near the last points with a measured rotational velocity.

Two possibilities were suggested to solve this controversy. One possibility is to identify the observed rotation velocity with the circular velocity, but this leads to the presence in galaxies of an extended population with a very high M/L. The other possibility is to assume that in the periphery of galaxies there exist non-circular motions which distort the rotation velocity.

To make a choice between the two possibilities for solving the mass discrepancy in galaxies more detailed models of galaxies were needed. In particular, it was necessary to take into account the presence in galaxies stellar populations with different physical properties (age, metal content, color, M/L value).

2.4 Mass Paradox in Galaxies from Galactic Models

Classical models of elliptical galaxies were found from luminosity profiles and calibrated using either central velocity dispersions, or motions of companion galaxies. The luminosity profiles of disks were often approximated by an exponential law, and bulge and halo dominated ellipticals by the de Vaucouleurs law.

Models of spiral galaxies were constructed using rotation velocities. As a rule, the rotation velocity was approximated by some simple formula, such as the Bottlinger law, or a polynomial. The other possibility was to approximate the spatial density (calculated from the rotation data) by a sum of ellipsoids of constant density (the Schmidt model). In the first case there exists a danger that, if the velocity law is not chosen well, then the density in the periphery of the galaxy may have unrealistic values (negative density or too high density, leading to an infinite total mass). If the model is built by superposition of ellipsoids of constant density, then the density is not a smooth function of the distance from the center of the galaxy. To avoid these difficulties Kuzmin developed models with a continuous change of the spatial density, and applied the new technique to M31 and our Galaxy. His method allows us to apply this approach also for galaxies consisting of several populations.

A natural generalization of classical galactic models is the use of all available observational data for spiral and elliptical galaxies, both photometric data on the distribution of color and light, and kinematical data on the rotation and/or velocity dispersion. Further, it is natural to apply identical methods for modeling of galaxies of different morphological type (including our own Galaxy), and to describe explicitly all major stellar populations, such as the bulge, the disk, the halo, as well as the flat population in spiral galaxies, consisting of young stars and interstellar gas.

All principal descriptive functions of galaxies (circular velocity, gravitational potential, projected density) are simple integrals of the spatial density. Therefore it is natural to apply for the spatial density $\rho(a)$ of galactic populations a simple generalized exponential law

$$\rho(a) = \rho(0) \exp(-(a/a_0)^{-1/N}) , \qquad (1)$$

where a is the semi-major axis of the isodensity ellipsoid, a_0 is the effective radius of the population, and N is a structural parameter, determining the shape of the density profile. This law (called Einasto profile) can be used for all galactic populations, including dark halos. The case N=4 corresponds to the de Vaucouleurs density law for spheroidal populations, N=1 corresponds to the exponential density law for disk.

Multi-component models for spiral and elliptical galaxies using photometric data were constructed by Freeman (1970). To combine photometric and kinematic data, mass-to-light ratios of galactic populations are needed. Luminosities and colors of galaxies in various photometric systems result from the physical evolution of stellar populations that can be modeled. Combined population and physical evolution models were calculated for a representative sample of galaxies by Tinsley (1968) and Einasto (1972, 1974). The last calculations showed that it was impossible to reproduce the rotation data by known stellar populations only. The only way to eliminate this conflict was *to assume the presence of an unknown population – corona – with a very high value of the mass-to-light ratio, and a large radius and mass*. Thus, the detailed modeling confirmed earlier results obtained by simpler models. But here we have one serious difficulty – no known stellar population has so large a M/L value.

Additional arguments for the presence of a spherical massive population in spiral galaxies came from the stability criteria against bar formation, suggested by Ostriker and Peebles (1973). Their numerical calculations demonstrated that initially very flat systems become rapidly thicker (during one revolution of the system) and evolve to a bar-like body. In real spiral galaxies a thin population exists, and it has no bar-like form. In their concluding remarks the authors write: *"Presumably even Sc and other relatively 'pure' spirals must have some means of remaining stable, and the possibility exists that those systems also have very large, low-luminosity halos. The picture developed here agrees very well with the fact, noted by several authors (see, for example, Brandt, Kalinowski, and Roosen 1972; Rogstad and Shostak 1972), that the mass-to-light ratio increases rapidly with distance from the center in these systems; the increase may be due to the growing dominance of the high mass-to-light halo over the low mass-to-light ratio disk. It also suggests that the total mass of such systems has been severely underestimated. In particular, the finding of Roberts and Rots (1973) that the rotation curves of several nearby spirals become flat at large distances from the nucleus may indicate the presence of very extended halos having masses that diverge rapidly [M(r) prop to r] with distance."*

3. Dark Matter in Astronomical Data

Modern astronomical methods yield a variety of independent information on the presence and distribution of dark matter. For our Galaxy, the basic data are the stellar motions perpendicular to the plane of the Galaxy (for the local dark matter), the motions of star and gas streams and the rotation (for the global dark matter). Important additional data come from gravitational microlensing by invisible stars or planets. In nearby dwarf galaxies the basic information comes from stellar motions. In more distant and giant galaxies the basic information comes from the rotation curves and the X-ray emission of the hot gas surrounding galaxies. In clusters and groups of galaxies the gravitation field can be determined from relative motions of galaxies, the X-ray emission of hot gas and gravitational lensing. Finally, measurements of fluctuations of the Cosmic Microwave Background (CMB) radiation in combination with data from type Ia supernovae in nearby and very distant galaxies yield information on the curvature of the Universe that depends on the amount of Dark Matter and Dark Energy.

Now we shall discuss these data in more detail.

3.1 Stellar Motions

The local mass density near the Sun can be derived from vertical oscillations of stars near the galactic plane, as was discussed before. Modern data by Gilmore, Wyse & Kuijken (1989) have confirmed the results by Kuzmin and his collaborators. Thus we come to the conclusion that *there is no evidence for the presence of large amounts of dark matter in the disk of the Galaxy*. If there is some invisible matter near the galactic plane, then its amount is small, of the order of 15 percent of the total mass density. The local dark matter is probably baryonic (low–mass stars or Jupiters), since non-baryonic matter is dissipationless and cannot form a highly flattened population. Spherical distribution of the local dark matter (in quantities suggested by Oort and Bahcall) is excluded since in this case the total mass of the dark population would be very large and would influence also the rotational velocity of the Galaxy at the location of the Solar System.

Additional information of the distribution of mass in the outer part of the Galaxy comes from streams of stars and gas. One of the streams discovered near the Galaxy is the Magellanic Stream of gas which forms a huge strip and connects the Large Magellanic Cloud (LMC) with the Galaxy. Model calculations emphasize that this stream is due to an encounter of the LMC with the Galaxy. Kinematical data for the stream are available and support the hypothesis on the presence of a massive halo surrounding the Galaxy. Recently, streams of stars have been discovered within the Galaxy as well as around our giant neighbor M31. Presently there are still few data on the kinematics of these streams.

Several measurements of the dark mass halo were also performed using the motion of the satellite galaxies or the globular clusters. Measurements indicate the mass of the dark halo of about $2\times10^{12} M_{\odot}$.

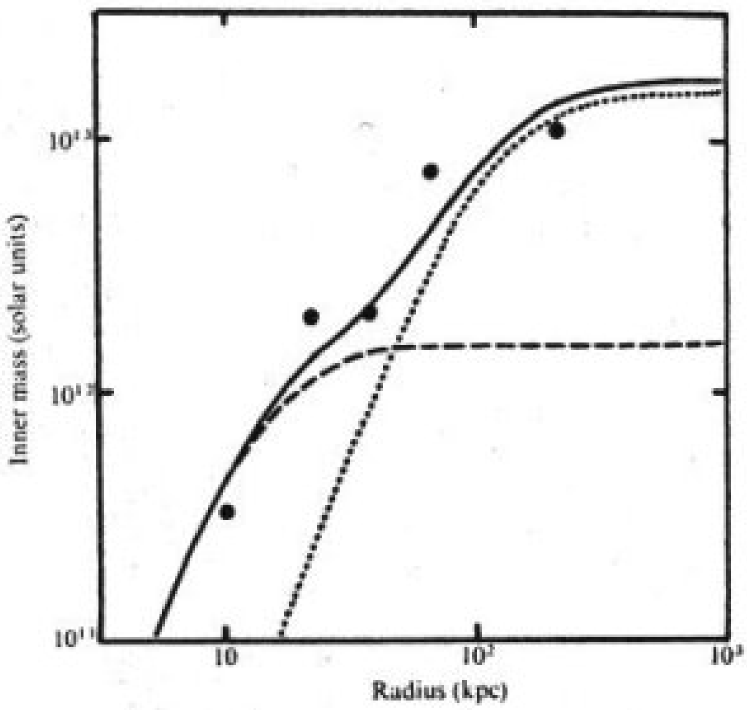

Figure 2. The mean internal mass $M(R)$ as a function of the radius R from the main galaxy in 105 pairs of galaxies (dots). Dashed line shows the contribution of visible populations, dotted line the contribution of the dark corona, solid line the total distribution (Einasto, Kaasik, Saar 1974).

However, significant progress is expected in the near future. The astronomical satellite GAIA (to fly in 2011) is expected to measure distances and photometric data for millions of stars in the Galaxy. When these data are available, more information on the gravitation field of the Galaxy can be found.

The motion of individual stars or gaseous clouds can be also studied in nearby dwarf galaxies. Determination of the dark halo was performed for over a dozen of them. Some of the newly discovered dwarfs, coming from the Sloan Digital Sky Survey, are very under-luminous but equally massive as the previously known dwarf galaxies in the Milky Way vicinity, which makes them good candidates for extreme examples of dark matter dominated objects. Also the studies of the disruption rate of these galaxies due to the interaction with the Milky Way impose limits to the amount of dark mass in these objects. The results indicate that the dark matter in these systems exceeds by a factor a few the mass of stars.

3.2 Dynamics and Morphology of Companion Galaxies

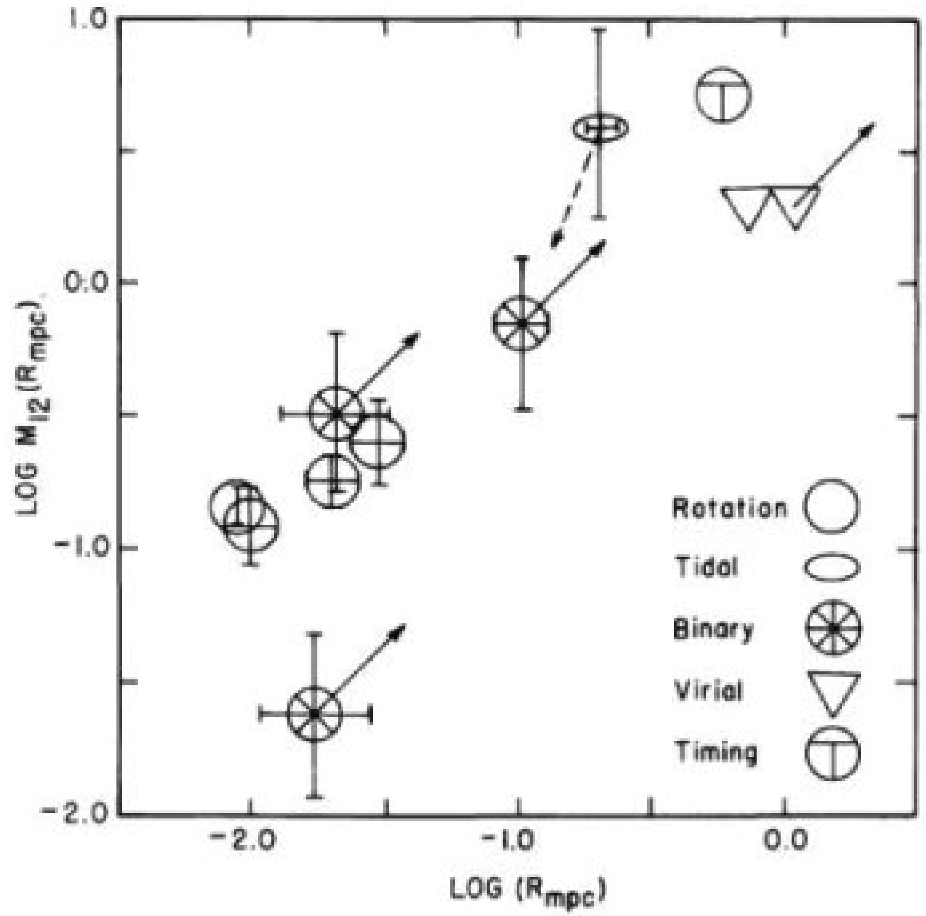

Figure 3. Masses (in units $10^{12}\ M_{\odot}$) of local giant galaxies (Ostriker, Peebles, and Yahil 1974, reproduced by permission of the AAS and authors).

The rotation data available in early 1970s allowed us to determine the mass distribution in galaxies up to their visible edges. In order to find how large and massive galactic coronas or halos are, more distant test particles are needed. If halos are large enough, then in pairs of galaxies the companion galaxies are located inside the halo, and their relative velocities can be used instead of the galaxy rotation velocities to find the distribution of mass around giant galaxies. This test was made independently by Einasto, Kaasik & Saar (1974) and Ostriker, Peebles & Yahil (1974), see Figs. 2 and 3. The paper by Ostriker et al. begins with the statement: *"There are reasons, increasing in number and quality, to believe that the masses of ordinary galaxies may have been underestimated by a factor of 10 or more"*. The closing statement of the Einasto et al. paper is: *"The mass of galactic coronas exceeds the mass of populations of known stars by one order of magnitude. According to new estimates the total mass density of matter in galaxies is 20% of the critical cosmological density."*

The bottom line in both papers was: since the data suggest that all giant galaxies have massive halos/coronae, dark matter must be the dynamically dominating population in the whole Universe.

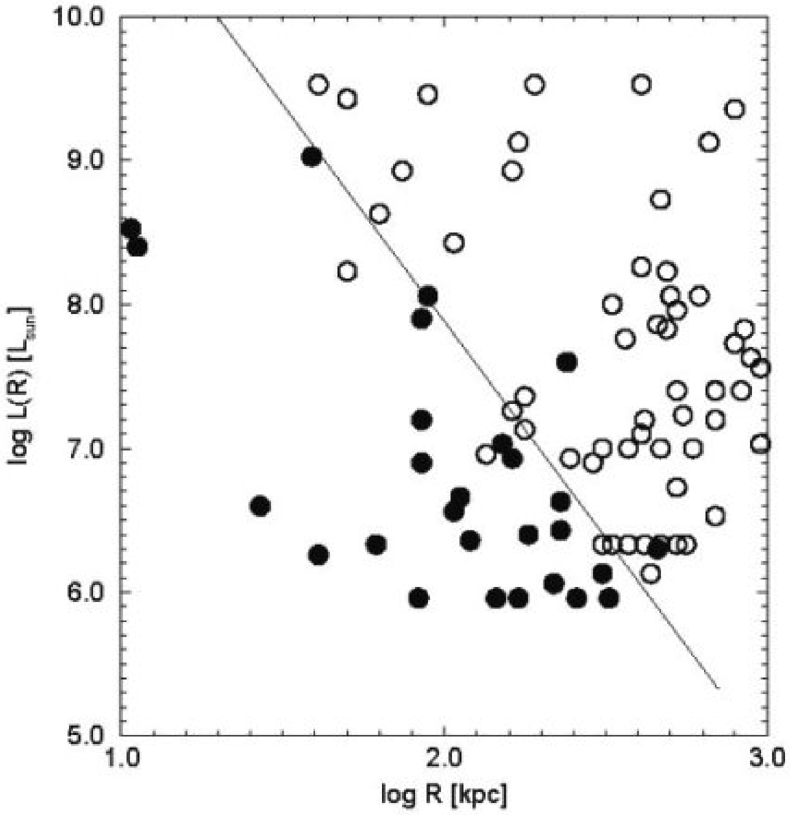

Figure 4. The distribution of luminosities of companion galaxies $L(R)$ at various distances R from the main galaxy. Filled circles are for elliptical companions, open circles for spiral and irregular galaxies (Einasto et al. 1974).

Results of these papers were questioned by Burbidge (1975), who noticed that satellites may be optical. To clarify if the companions are true members of the satellite systems, Einasto et al. (1974b) studied the morphology of companions. They found that companion galaxies are segregated morphologically: elliptical (non–gaseous) companions lie close to the primary galaxy whereas spiral and irregular (gaseous) companions of the same luminosity have larger distances from the primary galaxy; the distance of the segregation line from the primary galaxy depends on the luminosity of the satellite galaxy, Figure 4. This result shows, first of all, that the companions are real members of these systems – random by-fliers cannot have such properties. Second, this result demonstrates that diffuse matter has an important role in the evolution of galaxy systems. Morphological properties of companion galaxies can be explained, if we assume that (at least part of) the corona is gaseous.

Additional arguments in favor of physical connection of companions with their primary galaxies came from the dynamics of small groups. Their mass distribution depends on the morphology: in systems with a bright primary galaxy the density (found from kinematical data) is systematically higher, and in elliptical galaxy dominated systems it is also higher. The mass distribution found from the kinematics of group members smoothly continues the mass distribution of the primary galaxies, found from rotation data.

3.3 Extended Rotation Curves of Galaxies

The dark matter problem was discussed in 1975 at two conferences, in January in Tallinn (Estonia) and in July in Tbilisi (Georgia). The central problems discussed in Tallinn were: What is the physical nature of the dark matter? and: What is its role in the evolution of the Universe? Two basic models were suggested for coronas: faint stars or hot gas. It was found that both models have serious difficulties (see below).

In Tbilisi the Third European Astronomical Meeting took place. Here the principal discussion was between the supporters of the classical paradigm with conventional mass estimates of galaxies and of the new one with dark matter. The major arguments supporting the classical paradigm were summarized by Tammann. His most serious argument was: *Big Bang nucleosynthesis suggests a low-density Universe with the density parameter* $\Omega \approx 0.05$*; the smoothness of the Hubble flow also favors a low-density Universe.*

It was clear that by sole discussion the presence and nature of dark matter cannot be solved, new data and more detailed studies were needed. The first very strong confirmation of the dark matter hypothesis came from new extended rotation curves of galaxies.

In early 1970s optical data on rotation of galaxies were available only for inner bright regions of galaxies. Radio observations of the 21-cm line reached much longer rotation curves well beyond the Holmberg radius of galaxies. All available rotation data were summarized by Roberts in the IAU Symposium on Dynamics of Stellar Systems held in Besancon (France) in September 1974. Extended rotation curves were available for 14 galaxies; for some galaxies data were available until the galactocentric distance $\sim 40\ h^{-1}$ Mpc (we use in this paper the Hubble constant in the units of $H_0 = 100\,h$ kms $^{-1}$ Mpc $^{-1}$), see Figure 1 for M31. About half of galaxies had flat rotation curves, the rest had rotation velocities that decreased slightly with distance. In all galaxies the local mass-to-light ratio in the periphery reached values over 100 in Solar units. To explain such high M/L values Roberts assumed that late-type dwarf stars dominate the peripheral regions.

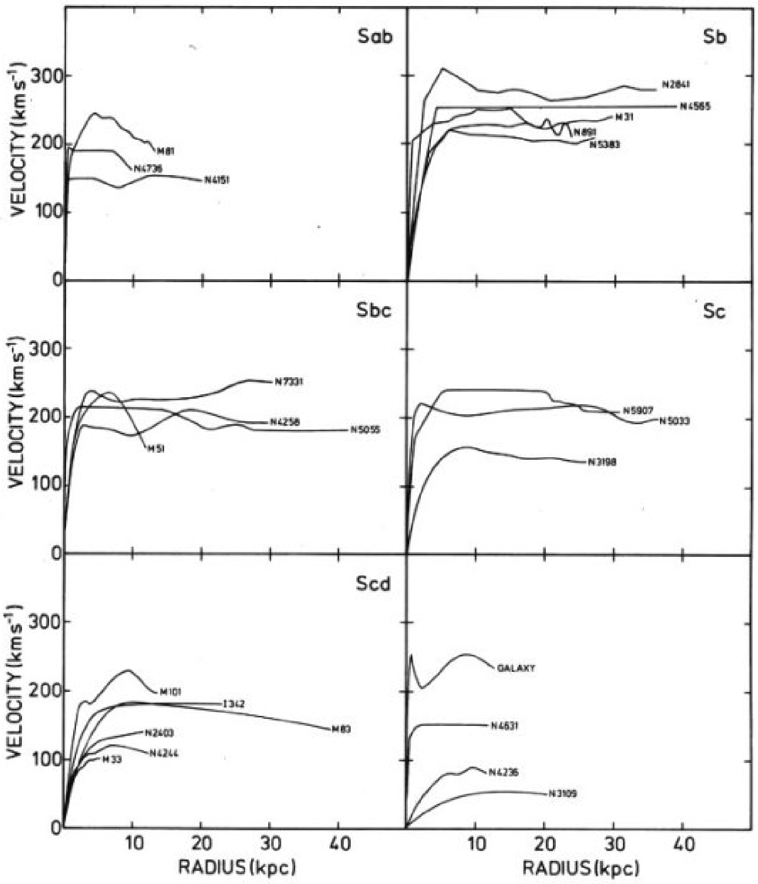

Figure 5: The rotation curves of spiral galaxies of various morphological type according to Westerbork radio observations (Bosma 1978, reproduced by permission of the author).

In mid-1970s measurements of a number of spiral galaxies with the Westerbork Synthesis Radio Telescope were completed, and mass distribution models were built, all-together for 25 spiral galaxies (Bosma 1978), Figure 5. Observations confirmed the general trend that the mean rotation curves remain flat over the whole observed range of distances from the center, up to ~ 40 kpc for several galaxies. The internal mass within the radius R increases over the whole distance interval.

At the same time Vera Rubin and her collaborators developed new sensitive detectors to measure optically the rotation curves of galaxies at very large galactocentric distances. Their results suggested that practically all spiral galaxies have extended flat rotation curves (Rubin, Ford & Thonnard 1978, 1980). The internal mass of galaxies rises with distance almost linearly, up to the last measured point; see Figure 6.

These observational results confirmed the concept of the presence of dark halos of galaxies with a high confidence.
Another very important measurement was made by Faber and collaborators (Faber et al. (1976, 1977, see also Faber & Gallagher 1979). They measured the central velocity dispersions for 25 elliptical galaxies and the rotation velocity of the Sombrero galaxy, a S0 galaxy with a massive bulge and a very weak population of young stars and gas

clouds just outside the main body of the bulge. Their data yielded for the bulge of the Sombrero galaxy a mass-to-light ratio $M/L = 3$, and for the mean mass-to-light ratios for elliptical galaxies about 7, close to the ratio for early type spiral galaxies. These observational data confirmed estimates based on the calculations of physical evolution of galaxies, made under the assumption that the lower mass limit of the initial mass function (IMF) is for all galactic populations of the order of $0.1 M_\odot$. These results showed that the mass-to-light ratios of stellar populations in spiral and elliptical galaxies are similar for a given color, and the ratios are much lower than those accepted in earlier studies based on the dynamics of groups and clusters. In other words, high mass-to-light ratios of groups and clusters of galaxies cannot be explained by visible galactic populations.

Earlier suggestions on the presence of mass discrepancy in galaxies and galaxy systems had been ignored by the astronomical community. This time new results were taken seriously. As noted by Kuhn, a scientific revolution begins when leading scientists in the field start to discuss the problem and arguments in favor of the new and the old paradigm.

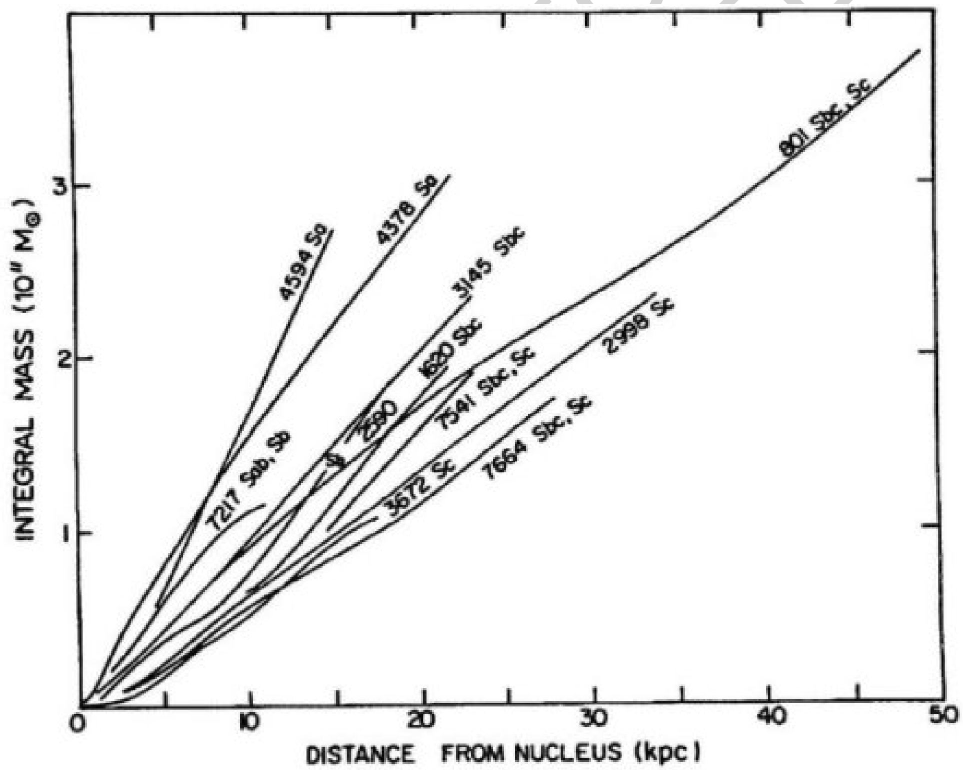

Figure 6. The integral masses as a function of the distance from the nucleus for spiral galaxies of various morphological type (Rubin, Ford & Thonnard 1978, reproduced by permission of the AAS and authors).

More data are slowly accumulating and new HI measurements from Westerbork extend the rotation curves up to 80 kpc (galaxy UGC 2487) or even 100 kpc (UGC 9133 and UGC 11852) showing flat rotation curves. The HI distribution in the Milky Way has been recently studied up to distances of 40 kpc by Kalberla et al. In 2008, the Milky

Way rotation curve has been determined by Xue et al. up to ~ 60 kpc from the study of ~ 2500 Blue Horizontal Branch stars from SDSS survey, and the rotation curves seems to be slightly falling from the 220 km s^{-1} value at the Sun location. Earlier determinations did not extend so far and extrapolations were affected by the presence of the ring-like structure in mass distribution at ~ 14 kpc from the center. Implied values of the dark matter halo from different measurements still differ between themselves by a factor 2 - 3, being in the range from $10^{12} - 2.5\times10^{12} M_{\odot}$.

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Jaan Einasto, born in Tartu, Estonia, 23 February 1929. Graduated 1947 Tartu 1st High School (Treffner Gymnasium), in 1952 Tartu University cum laude. PhD in 1955 in Tartu University on stellar kinematics, Doctor of Science in 1972 in Tartu University on 'Structure and evolution of regular galaxies'. Major fields of study: stellar kinematics; structure and evolution of galaxies; dark matter; large-scale distribution of galaxies and clusters of galaxies; evolution of the large-scale structure.

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