

## Two hundred years of galactic studies in Tartu Observatory

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An overview is provided for 200 years of galactic studies at the Tartu Observatory. Galactic studies have been one of the main topics of studies in Tartu over the whole period of the history of the Observatory, starting from F.G.W. Struve and J.H. Mädler, followed by Ernst Öpik and Grigori Kuzmin, and continuing with the present generation of astronomers. Our goal was to understand better the structure, origin and evolution of stars, galaxies and the Universe.

*Keywords:* Dark matter; galaxies; clusters of galaxies; large-scale structure of the Universe

### 1. Introduction

Galactic studies have been one of the main topics of the Tartu Observatory over the whole period of its existence. These studies began with the work by F.G.W. Struve on double stars and measurements of stellar parallaxes in early 19th century, when Tartu Observatory was founded in the "Kaiserliche Universität zu Dorpat". Modern era of Galactic studies began about 95 years ago when Ernst Öpik determined the dynamical density of matter in the disk of the Galaxy in 1915, the distance to the Andromeda Nebula in 1922, and found main principles of stellar structure and evolution in 1938. His student Grigori Kuzmin developed principles of Galactic modeling and calculated the local density of matter near the Sun, suggesting the absence of local dark matter in large quantities. The present generation of astronomers follows these traditions.

In the following I give an overview of the development of the ideas of the structure of galaxies and the Universe over the whole period of activity of the Tartu Observatory. The period of last 50 years is described in more detail.

### 2. Tartu Observatory 1810 - 1960

#### 2.1. *F. G. W. Struve, stellar distances and the Meridian Arc*

It was a tradition in classical universities to have an astronomical observatory. Tartu University Observatory was built in 1810, its astronomical instruments were installed by astronomy and mathematics student Friedrich Georg Wilhelm Struve (1793 - 1864), who after defending his PhD was nominated to professor of astronomy and mathematics and director of the observatory. Struve understood well the needs of contemporary astronomy and geodesy. The main goal at this time was to understand the nature of stars and stellar systems. Struve started to measure stellar positions, which was basis for better description of the universe. He soon realised that conventional astronomical instruments, available in Tartu, were not sufficient to solve most interesting problems. Thus he applied to get support to buy a new larger telescope. His efforts succeeded and in 1825 a 9 inch Fraunhofer refractor was



Fig. 1. Left: F.G.W Struve. Right: Map of Struve Meridian Arc through Tartu Observatory

installed in Observatory. For about 15 years this was the largest and best telescope of this type in the world.

Struve made excellent use of the new telescope. First he made a survey of the whole Northern sky and published a catalogue of double stars detected. A catalogue followed, which contained exact measurements of positions of double stars.<sup>1</sup> After repeated observations have been made it is possible to calculate orbits of double stars and to get information on their masses. This is a foundation of the new astronomy – astrophysics. As a by-product of the measurements of double stars he also published his determination of the distance of a star – Vega. With this measurement it was finally demonstrated that stars are distant suns. Struve double star catalogue is used even in present days, his achievements have found place in astronomy textbooks.

Another important scientific-historic achievement of F.G.W. Struve was the astronomic-trigonometric measurement of Tartu (Struve) Meridian Arc (1816-1852). This measurement was made together with Carl Friedrich Tenner (1783 - 1859). They succeeded in determining the almost 3000 km long section of the Meridian Arc between the mouth of Danube and the Arctic Ocean with the accuracy of  $\pm 12$  m.<sup>2</sup> The comparison of data of different arc sections indicated that the length of arc, corresponding to one degree of latitude, increases towards the pole, i.e. the Earth is flattened. The measurements were used by F.W. Bessel for determination of spheroidal Earth's new parameters. Struve geodetic Meridian Arc is included to the UNESCO World Heritage List.

In 1839 F.G.W. Struve was appointed director of the new Pulkovo Observatory.

The next director of Tartu Observatory Johann Heinrich Mädler (1794 - 1874) was interested in the dynamics of the Milky Way. In his book "Centralsonne" he tried to determine the center of the Galaxy using proper motions of stars. The accuracy of data was not sufficient for this task, the method itself is correct.

## 2.2. *Ernst Öpik, the nature of galaxies and the evolution of stars*



Fig. 2. Ernst Öpik, his wife and author in 1970 at the IAU General Assembly in Brighton. Andromeda nebula M31.

The founder of the modern astronomy school in Tartu University was Ernst Öpik (1893 - 1985). He started his astronomical career as student of the Moscow University, and made his principal discoveries as observator of the Tartu University Observatory. One of his first scientific papers was devoted to the question: What is the density of matter near the plane of the Milky Way stellar system? His calculations showed that the gravitating matter density can be fully explained by observable stars, and that there is no evidence for hypothetical matter near the symmetry plane of the Galaxy. This work seems to be the first attempt to address the dark matter problem.<sup>3</sup>

Next Öpik devoted his attention to spiral nebulae. Their nature was not known at this time: Are they gaseous objects within the Milky Way or distant worlds similar in structure to our Galaxy? Immediately when relative velocity measurements of the central part of Andromeda nebula M31 had been published, Öpik developed a method how to use this information to estimate the distance to M31. His result was 440 kpc (about 1.5 million light years).<sup>4</sup> With this work he solved the problem of the nature of spiral nebulae, and showed that the universe is millions of times larger than our Milky Way system.

Another unsolved problem at this time was the source of stellar energy and the evolution of stars. Already in early 1920s Öpik demonstrated, using very simple physical considerations, that gravitational contraction and radioactivity cannot be the main sources of stellar energy. He concluded, that some unknown subatomic

processes in central regions of stars must be responsible for stellar energy. When data on atomic structure were available, he developed a detailed theory of stellar evolution, based on nuclear reactions in stellar interiors. Here under very high temperature hydrogen burns to helium, and huge amounts of energy will be released.<sup>5</sup> The efficiency of these reactions has just been estimated based on atomic theory, thus Öpik was able to calculate ages of stars. He demonstrated, that hot giant stars are so luminous that their energy sources will be exhausted within several tens millions years. Their presence shows that they have been recently formed – in other words, star formation is a process which takes place even today.

These results revolutionised our understanding of stars and their evolution. Presently they are accepted by the astronomical community. Professor of astronomy in Tartu University Rootsmäe (1885 - 1959) applied these ideas to kinematics of stars to find the sequence of formation of different stellar populations.<sup>6</sup> Similar ideas were developed independently by Eggen, Lynden-Bell and Sandage.<sup>7</sup>

### 2.3. Grigori Kuzmin, the density of matter and galactic dynamics

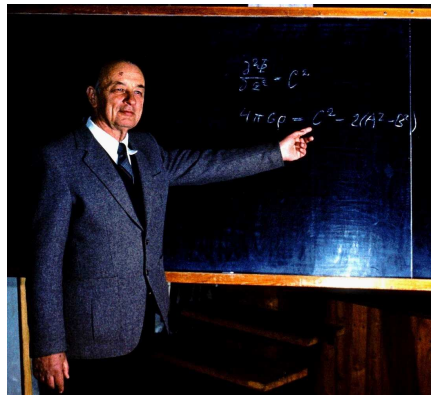


Fig. 3. Grigori Kuzmin explaining his method to determine the density of matter near the Sun

Öpik's student Grigori Kuzmin (1917 - 1988) continued his mentors work on studying the structure of the Galaxy. In his PhD thesis he developed further Öpik's method to derive the density of matter in the Galaxy and constructed a mathematical model of the Galaxy, much more advanced than previous ones.<sup>8-11</sup> In contrast to earlier models by Oort and Schmidt he used ellipsoids of variable density, and applied the theory first to the Andromeda galaxy and then to our own Galaxy. One of central problems in modeling the Galaxy was the density of matter near the Sun. In 1930s famous Dutch astronomer Jan Oort<sup>12</sup> studied this problem and found, that in addition to ordinary stars there must be in the Galaxy an unknown population, so that the total local density exceeds twice the density of visible matter. Kuzmin found that the method used by Oort is not very accurate and that there is no in-

dication for the presence of local dark matter in the Galaxy. Later two students of Kuzmin, Heino Eelsalu (1930 - 1998)<sup>13</sup> and Mihkel Jõeveer (1937 - 2006),<sup>14,15</sup> reanalysed the problem, using different data and methods, and confirmed his results.

The discrepancy between results of Tartu astronomers and the rest of the world continued until 1990s, when finally modern data confirmed that Kuzmin was right (Gilmore, Wyse & Kuijken<sup>16</sup>). Thus we came 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 it consists probably of low-mass stars or jupiters, which have been formed from the flat gas population.

Kuzmin also developed a method how to describe more accurately the kinematics of stellar populations, using three integrals: the energy and mass conservation integrals, and a third integral, which allows the existence of three-axial velocity ellipsoids of stellar populations.<sup>9,11</sup> From his model it follows that orbits of stars in galaxies lie in a toroidal volume. Numerical modeling of star orbits in realistic mass models have confirmed Kuzmin's prediction.

### 3. Following Öpik and Kuzmin: detailed galactic models

#### 3.1. *Methods of galactic modeling*

The work by Öpik, Rootsmäe, Kuzmin and their students formed the basis of a concept of the structure and evolution of stellar populations in galaxies, which is rather close to the presently accepted picture. In early 1960s I was interested in the problem too. As new observational data arrived, the need for a better and more accurate model of our Galaxy and other galaxies was evident. Detailed local structure is known only for our own Galaxy, and global information on stellar populations is better known for external galaxies, thus it is reasonable to investigate the structure of our Galaxy and other galaxies in parallel.

Also there was a need for a more detailed method of the construction of composite models of galaxies. This goal was realised in a series of papers in Tartu Observatory Publications,<sup>17-21</sup> a summary of the method was published in English.<sup>22</sup> A natural generalisation of classical galactic models is the use of all available observational data for spiral and elliptical galaxies, both photometric data on the distribution of colour 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.

The main principles of model construction were: (1) galaxies can be considered as sums of physically homogeneous populations (young flat disk, thick disk, core, bulge, halo); (2) physical properties of populations (mass-to-luminosity ratio  $M/L$ , colour) should be in agreement with models of physical evolution of stellar populations; (3) the density of a population can be expressed as ellipsoids of constant flatness and rotational symmetry; (4) densities of populations are non-negative and finite; (5) moments of densities which define the total mass and ef-

fective radius of the galaxy are finite. It was found that in a good approximation densities of all stellar populations can be expressed by a generalised exponential law:  $\rho(a) = \rho(0) \exp[-(a/a_c)^{1/N}]$ , where  $\rho(0) = hM/(4\pi\epsilon a_0^3)$  is the central density,  $a = \sqrt{R^2 + z^2/\epsilon^2}$  is the distance along the major axis,  $\epsilon$  is the axial ratio of the equidensity ellipsoid,  $a_c = ka_0$  is the core radius ( $a_0$  is the harmonic mean radius),  $h$  and  $k$  are normalising parameters, depending on the structural parameter  $N$ , which allows to vary the density behaviour with  $a$ . The cases  $N = 1$  and  $N = 4$  correspond to conventional exponential and de Vaucouleurs models, respectively.

This density law (called Einasto profile) was first applied to find a composite model of the Galaxy,<sup>23</sup> based on the new system of Galactic constants, using all available data (Einasto and Kutuzov<sup>24</sup>). Next the method was applied to the Andromeda galaxy.<sup>25–27</sup>

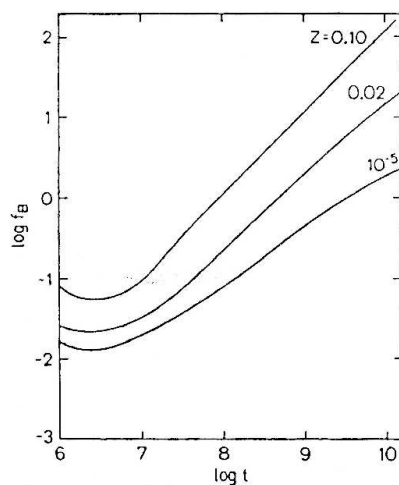


Fig. 4. The evolution of mass-to-luminosity ratios  $f_B = M/L$  for populations of various age  $t$  and metal content  $Z$ , according to model calculations.<sup>31</sup>

A central problem in galactic modeling is the correct estimation of the mass-to-luminosity ratio of populations. This ratio depends on the evolutionary history of the population and on its chemical composition. In order to bring these ratios for different populations to a coherent system, a model of physical evolution of stellar populations was developed.<sup>28,31</sup> The model used as input data the evolutionary tracks of stars of various composition (metallicity) and age; the star formation rate as a function of stellar mass was accepted according to Salpeter,<sup>29</sup> with a low-mass limit of star formation of  $M_0 \approx 0.03 M_\odot$ . The model yielded a continuous sequence of population parameters as a function of age (colour, spectral energy distribution,  $M/L$ ), see Fig. 4. The results of modeling stellar populations were calibrated using direct dynamical data for star clusters and central regions of galaxies (velocity dispersions) by Einasto & Kaasik.<sup>30</sup> These data supported relatively high values

( $M/L \approx 10 - 30$ ) for old metal-rich stellar populations near centres of galaxies; moderate values ( $M/L \approx 3 - 10$ ) for discs and bulges; and low values ( $M/L \approx 1 - 3$ ) for metal-poor halo-type populations. Modern data yield lower values, due to more accurate measurements of velocity dispersions in clusters and central regions of galaxies, and rotation data on bulge dominated S0 galaxies.

## 4. Dark matter in galaxies

### 4.1. Masses and radii of galaxies

I had a problem in the modeling of M31. If rotation data were taken at face value, then it was impossible to represent the rotational velocity with the sum of known stellar populations. The local value of  $M/L$  increases towards the periphery of M31 very rapidly, if the mass distribution is calculated directly from rotation velocity. All known old metal-poor halo-type stellar populations have a low  $M/L \approx 1 - 3$ . In contrast, on the basis of rotation data we got  $M/L > 1000$  on the periphery of the galaxy near the last point with measured rotational velocity.

I discussed the problem with my collaborator Enn Saar. He suggested to abandon the idea, that only stellar populations exist in galaxies. Instead it is reasonable to assume the existence of a population of unknown nature and origin, and to look which properties it should have using available data on known stellar populations. So I calculated a new set of models for M31, our Galaxy and several other galaxies of the Local Group, as well as for the giant elliptical galaxy M87 in the Virgo cluster. In most models it was needed to include a new population in order to bring rotation and photometric data into mutual agreement. To avoid confusion with the metal-poor halo the new hypothetical population was called corona.

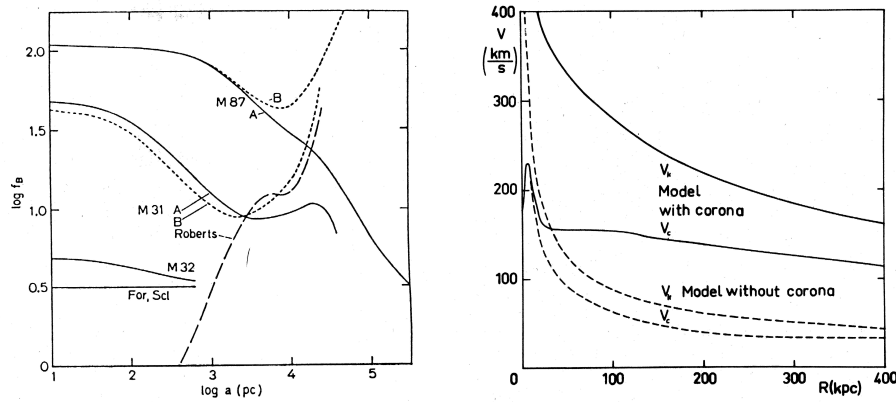


Fig. 5. Combined physical and evolution models of M31, M32, M87, For, Scl. Left: mass-to-luminosity ratio as a function of radius. Models without and with massive corona are shown, cases A and B, respectively.<sup>31</sup> Right: circular and escape velocities of for a model of the Galaxy with and without a corona.<sup>39</sup>

Results of these calculations were reported in the First European Astronomy Meeting in Athens in September 1972.<sup>31</sup> The conclusions were: (1) There are two dark matter (DM) problems: the local DM near the Galactic plane, and the global DM forming an extended almost spherical population (corona); (2) The local dark matter, if it exists, must be of stellar origin, as it is strongly concentrated to the Galactic plane; (3) The global dark matter is probably of non-stellar origin. Available data were insufficient to determine outer radii and masses of coronas. Preliminary estimates indicated that in some galaxies the mass and radius of the corona may exceed considerably the mass and radius of known stellar populations.

Arguments for the non-stellar origin of galactic coronas were the following. (1) Physical and kinematical properties of the stellar populations depend almost continuously on the age of the population, the oldest have the lowest metallicity and  $M/L$ -ratio, and there is no place where to put the corona into this sequence.<sup>31</sup> (2) Since the  $M/L$  value and spatial distribution of the corona differ so much of similar properties of known stellar populations, the corona must have been formed much earlier than all known populations; the total mass of the corona exceeds masses of known populations by an order of magnitude, thus we have a problem: How to transform in an early stage of the evolution of the universe most of gas to the coronal stars? It is known that star formation is a very inefficient process, as in a star-forming gaseous nebula only about 1 % of matter transforms to stars.<sup>31</sup> (3) Due to the large size of the corona, coronal stars must have in the vicinity of the Sun much higher velocities than all other stars, but no extremely high-velocity stars have been found by Jaaniste and Saar.<sup>33</sup> (4) Luminosity decreases in outer regions rapidly, therefore, if the matter is in stars, they must be of very low luminosity. The presence of low-luminosity stars in outer galactic regions without bright ones would require a process of large-scale segregation of stars according to mass (low-luminosity stars have small masses), but this is highly improbable.<sup>31</sup> The hidden matter cannot be in the form of neutral gas, since this gas would be observable.<sup>31</sup> For these reasons, I assumed that coronas may consist of hot gas. Soon it was clear that a fraction of coronal matter is indeed gaseous,<sup>36</sup> however not all.

To find the radii and masses of galactic coronas more distant test objects are needed. One possibility is the use of companion galaxies. If coronas are large enough, then in pairs of galaxies the companion galaxy is moving inside the corona, and it can be considered as a test particle to measure the gravitational attraction of the main galaxy. Mean relative velocities, calculated for different distances from the main galaxy, can be used instead of rotation velocities to find the mass distribution of giant galaxies. A collection of 105 pairs of galaxies yield following results: radii and masses of galactic coronas exceed radii and masses of stellar populations of galaxies by an order of magnitude! Together with A. Kaasik and E. Saar we calculated new models of galaxies including dark coronas. Results were reported in the Caucasus Winter School in January 1974, and published in *Nature*.<sup>34</sup> Our data suggest that all giant galaxies have massive coronas of some unknown origin (Dark Matter), the total masses of galaxies including dark coronas exceed masses of known populations



by an order of magnitude. It follows, that dark matter is the dominating component in the whole universe. Similar results have been obtained by Ostriker, Peebles and Yahil.<sup>35</sup> Additional arguments supporting the physical connection between main galaxies and their companions were found from the morphology of companions.<sup>36</sup>

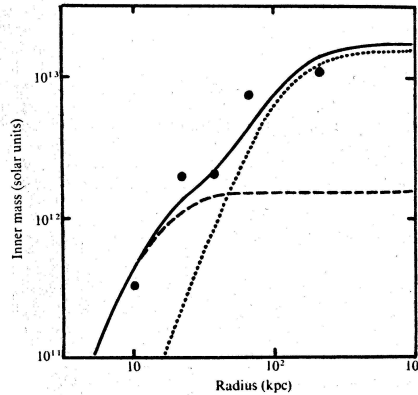


Fig. 6. Internal mass of galaxies: dots - data on 105 companion galaxies; dashed line - mass due to known galactic populations; dotted line - mass due to dark corona; solid line - total internal mass from models.<sup>34</sup>

#### 4.2. Problems with dark matter

In January 1975 the first conference on dark matter was held in Tallinn, Estonia. The rumour on dark matter had spread around the astronomical community and, in contrast to conventional local astronomy conferences, leading Soviet astronomers and physicists attended. The main topics was the possible nature of the dark matter. It was evident that a stellar origin is almost excluded,<sup>33</sup> but a fully gaseous corona also has difficulties, as shown by Komberg and Novikov.<sup>37</sup> The problems with baryon nucleosynthesis constraints were discussed by Zeldovich. So the nature of DM was not clear.

The next dark matter discussion was in July 1975 during the Third European Astronomical Meeting in Tbilisi, Georgia, where a full session was devoted to the dark matter problem. 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 summarised by Gustav Tammann.<sup>38</sup> The most serious arguments were: *Big Bang nucleosynthesis suggests a low-density Universe with the density parameter  $\Omega \approx 0.05$ ; the smoothness of the Hubble flow also favours a low-density Universe.*

Dark matter problem was also discussed during the IAU General Assembly in Grenoble, 1976. Here arguments for the non-stellar nature of dark coronas were again presented.<sup>32</sup>

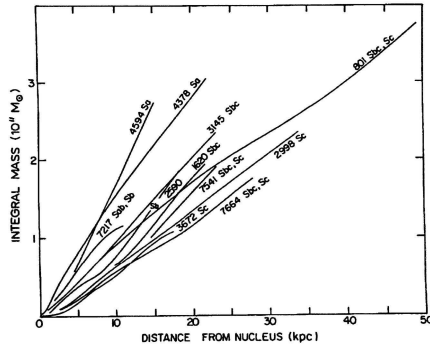


FIG. 6.—Integral mass within disk of radius  $r$ , as a function of  $r$ , for 11 galaxies, Sa through Sc, out to last measured velocity. Scale gives mass for disk models; masses for spherical galaxies are 1.4 times larger. Linear increase of mass with radius is a consequence of flat rotation curves. Mass gradient,  $dM/dr$ , is greater for early types, but total mass is a function both of  $V^2$  and  $r$ . Surface mass density decreases systematically with Hubble type.

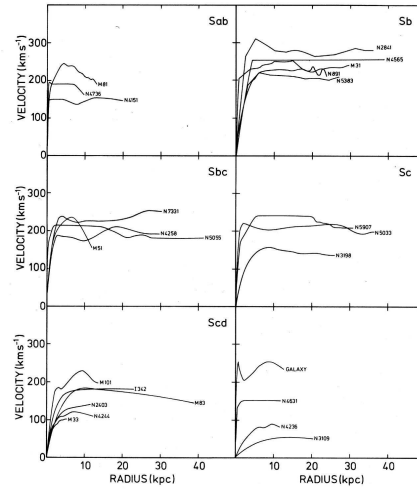


Figure 2 Rotation curves of 25 galaxies of various morphological types from Bosma (1978).

Fig. 7. Left: Integral masses of spiral galaxies, derived by Rubin et al.<sup>40</sup> Right: rotation curves of 25 spiral galaxies by Bosma.<sup>42</sup>

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. A very strong confirmation of the dark matter hypothesis came from new extended rotation curves of galaxies. 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.<sup>40,41</sup> The internal mass of galaxies rises with distance almost linearly, up to the last measured point, see Fig. 7. At the same time 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 by Bosma,<sup>42</sup> see Fig. 7. Observations confirmed the general trend that the mean rotation curves remain flat over the whole observed range of distances from the center, up to  $\sim 40$  kpc for several galaxies.

These new observations confirmed the presence of dark coronas of galaxies. However, the nature of the coronas was still unclear, and the difficulties discussed in Tallinn and Tbilisi were not clarified.

#### 4.3. Non-baryonic nature of Dark Matter

In late 1970s suggestions were made that some sort of non-baryonic elementary particles may serve as candidates for dark matter particles. There were several reasons to search for non-baryonic particles as a dark matter candidate. First of all, no baryonic matter candidate did fit the observational data. Second, the total amount of dark matter is of the order of 0.2–0.3 in units of the critical cosmological density, whereas the nucleosynthesis constraints suggest that the amount of baryonic

matter cannot be higher than about 0.04 of the critical density.

A very important observation was made, which caused doubts to the baryonic matter as the dark matter candidate. In 1964 Cosmic Microwave Background (CMB) radiation was detected. Initially the Universe was very hot and all density and temperature fluctuations of the primordial gas were damped by very intense radiation. At a certain epoch called recombination the gas became neutral, and density fluctuations in the gas had a chance to grow by gravitational instability. But gravitational clustering is a very slow process. In order to have time to build up all observed structures the amplitude of initial density fluctuations at the epoch of recombination must be of the order of  $10^{-3}$  of the density itself. Density fluctuations are of the same order as temperature fluctuations, and astronomers started to search for temperature fluctuations of the CMB radiation. None were found. As the accuracy of measurement increased, lower and lower upper limits for the amplitude of CMB fluctuations were obtained. In late 1970s it was clear that the upper limits are much lower than the theoretically predicted limit  $10^{-3}$ .

Then astronomers recalled the possible existence of non-baryonic particles, such as heavy neutrinos. This suggestion was made independently by several astronomers (<sup>43–46</sup>). If dark matter is non-baryonic, then this helps to explain the paradox of small temperature fluctuations of cosmic microwave background radiation. Density perturbations of non-baryonic dark matter start growing already during the radiation-dominated era, whereas the growth of baryonic matter is damped by radiation. If non-baryonic dark matter dominates dynamically, the total density perturbations can have an amplitude of the order  $10^{-3}$  at the recombination epoch, which is needed for the formation of the observed structure of the Universe. The evolution of perturbations in a neutrino-dominated dark matter medium was discussed in a conference in Tallinn in April 1981 (this conference was probably the first one devoted to the astro–particle physics).

Numerical simulations made for a neutrino-dominated universe were made by a number of astronomers. These calculations demonstrated some weak points in the scenario: large-scale structures (superclusters) form too late and have no fine structure as observed in the real Universe. A new scenario was suggested, among others, by Bond, Szalay & Turner;<sup>47</sup> here hypothetical particles like axions, gravitinos or photinos play the role of dark matter. Numerical simulations of structure evolution for neutrino and axion-dominated universe were made and analysed by Melott et al.<sup>48</sup> All quantitative characteristics (connectivity of the structure, multiplicity of galaxy systems, correlation function) of this new model fit the observational data well. This model was called subsequently the Cold Dark Matter (CDM) model, in contrast to the neutrino-based Hot Dark Matter model. Presently the CDM model with some modifications is the most accepted model of the structure evolution (Blumenthal et al.<sup>49</sup>).

## 5. Large scale structure of the Universe

### 5.1. Zeldovich question

After my talk in the Caucasus Winter School Zeldovich turned to me and offered collaboration in the study of the universe. He was developing a theory of the formation of galaxies – the pancake theory;<sup>50</sup> an alternative whirl theory was suggested by Ozernoy, and a third theory of hierarchical clustering by Peebles. Zeldovich asked for our help in solving the question: Can we find some observational evidence which can be used to discriminate between these theories?

Initially we had no idea how we can help Zeldovich. But soon we remembered our previous experience in the study of galactic populations: kinematical and structural properties of populations hold the memory of their previous evolution and formation (Rootsmäe,<sup>6</sup> Eggen, Lynden-Bell & Sandage<sup>7</sup>). Random velocities of galaxies are of the order of several hundred km/s, thus during the whole lifetime of the Universe galaxies have moved from their place of origin only about  $1 h^{-1}$  Mpc (we use the Hubble constant in units  $H_0 = 100 h \text{ km s}^{-1} \text{ Mpc}^{-1}$ ). In other words – if there exist some regularities in the distribution of galaxies, these regularities must reflect the conditions in the Universe during the formation of galaxies.

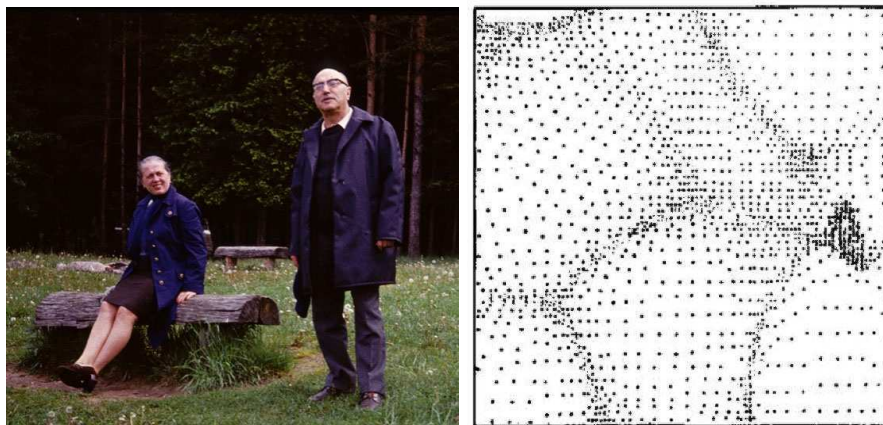


Fig. 8. Left: Zeldovich with his wife visiting Estonia. Right: Distribution of particles in simulation (Zeldovich group 1975).

In our work to solve the Zeldovich question we had a close collaboration with his team. In 1975 Doroshkevich, Shandarin and Novikov<sup>51</sup> obtained first results of numerical simulations of the evolution of particles according to the theory of gravitational clustering, developed by Zeldovich.<sup>50</sup> This was a 2-dimensional simulation with  $128 \times 128$  particles (see Fig. 8). In this picture a system of high- and low-density regions was seen: high-density regions form a cellular network, which surrounds large under-dense regions. One of our challenges was to find out, whether the real distribution of galaxies showed some similarity with the theoretical picture.

Now we had a guiding idea how to solve the problem of galaxy formation: *We have to study the distribution of galaxies on larger scales.*

### 5.2. Tallinn Symposium on Large Scale Structure of the Universe

Both our galactic astronomy and theoretical cosmology teams participated in the effort to find the distribution of galaxies and their systems in space. One approach was the study of the distribution of nearby Zwicky clusters. Many bright galaxies of nearby Zwicky clusters had at this time measured redshifts, so we hoped to determine the distribution of clusters and to find some regularities there. To see the distribution better, we built in the office of Saar and Jaaniste a 3-dimensional model from plastic balls. Some regularity was evident: there were several clusters of Zwicky clusters – superclusters, one of them in the Perseus region. But too many clusters had no galaxies with measured redshifts, so it was difficult to get an overall picture. Zwicky nearby clusters were used several years later by Einasto, Jõeveer & Saar,<sup>52</sup> when more redshifts were available and for the rest photometric distances were estimated.



Fig. 9. Left: Enn Saar. Right: Mihkel Jõeveer.

A different approach was used by Mihkel Jõeveer. He used wedge-diagrams. His trick was: he made a number of wedge diagrams in sequence for fixed  $\alpha$  and  $\delta$  intervals, and plotted in the same diagram galaxies, as well as groups and clusters of galaxies, and Markarian galaxies. Redshift data for clusters, groups and Markarian galaxies were almost complete in the Northern hemisphere up to a redshift about 15.000 km/s. Two wedge-diagrams of width  $\Delta\delta = 15^\circ$ , crossing the Coma, Perseus, Hercules and Local superclusters, are shown in Fig. 10. In these diagrams a regularity was clearly seen: *isolated galaxies and galaxy systems populate identical regions, and the space between these regions is empty.* After this success the whole Tartu

cosmology team continued the study using wedge-diagrams and other methods to analyse the distribution of galaxies and their systems. A detailed analysis of the Perseus supercluster region was made; here the number of foreground galaxies is very small.

Already in 1975, after the Tbilisi Meeting, we discussed with Zeldovich the possibility to organise a real international conference devoted solely to cosmology. Due to Soviet bureaucratic system it was extremely difficult for Soviet astronomers to attend international conferences in Western countries; thus the only possibility to have a better contact between cosmologists from East and West was to hold the conference within the Soviet Union. Zeldovich suggested to hold it in Tallinn. After some discussion we decided to devote it to “Large Scale Structure of the Universe”. When we started preparations we had no idea what this term could mean.

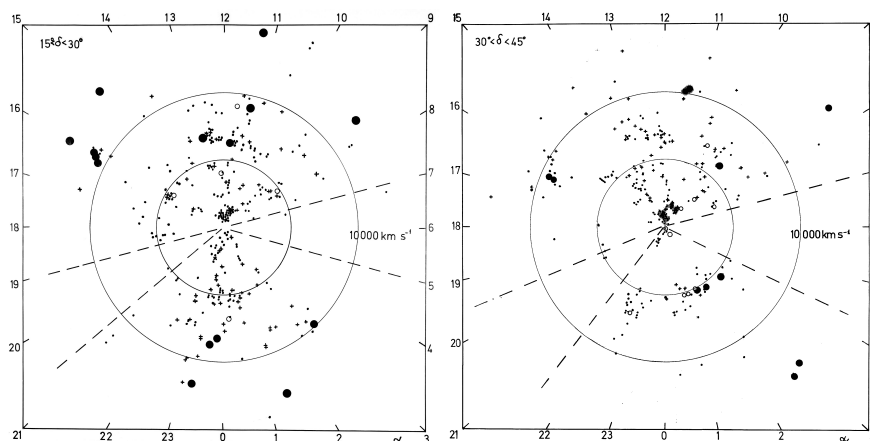


Fig. 10. Clusters, groups and bright galaxies are mostly located in chains, concentrated to superclusters, weaker galaxy chains bind superclusters to infinite network. The space between galaxy-cluster chains is empty - these regions are called holes or cosmic voids (Jõeveer & Einasto<sup>53</sup>)

The symposium was held in September 1977. Our main results were presented in the talk by Jõeveer & Einasto:<sup>53</sup> (1) galaxies, groups and clusters of galaxies are not randomly distributed, but form chains, concentrated in superclusters; (2) the space between galaxy chains contains almost no galaxies and form holes or voids of diameter up to  $\approx 70 h^{-1} \text{ Mpc}$  (see Fig. 10); (3) the whole pattern of the distribution of galaxies and clusters resembles cells of a honeycomb, rather close to the picture predicted by Zeldovich. A more detailed analysis was published separately by Jõeveer, Einasto & Tago.<sup>54</sup>

The presence of voids in the distribution of galaxies was reported also by other groups: by Tully & Fisher,<sup>55</sup> Tift & Gregory,<sup>56</sup> and Tarenghi et al.<sup>57</sup> in the Local, Coma and Hercules superclusters, respectively. Theoretical interpretation of the observed cellular structure was discussed by Zeldovich.<sup>58</sup> Malcolm Longair noted in

his concluding remarks: *the discovery of the filamentary character of the distribution of galaxies, similar to a lace-tablecloth, and the overall cellular picture of the large-scale distribution was the most exciting result presented at this symposium.* These results demonstrated that the pancake scenario by Zeldovich<sup>50</sup> has many advantages over other rivalling scenarios. The term “Large-Scale Structure of the Universe” got its present meaning.

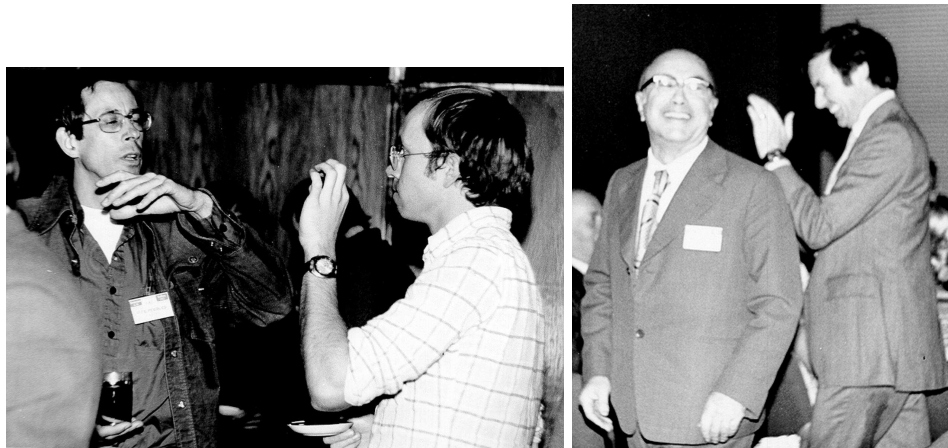


Fig. 11. Participants of the Tallinn Symposium on the Large Scale Structure of the Universe. Left: Peebles and Tremaine; Right: Zeldovich and Longair.

### 5.3. Understanding the large-scale structure of the Universe

The first problem to solve was to find some explanation for the absence of galaxies in voids. This was done by Einasto, Jõeveer & Saar.<sup>52</sup> Saar developed an approximate model of the evolution of density perturbations in under- and over-dense regions based on Zeldovich ideas. He found that the matter flows out of under-dense regions and collects in over-dense regions until it collapses (pancake forming) and forms here galaxies and clusters. In under-dense regions the density decreases continuously, but never reaches zero: there must be primordial matter in voids. In these under-dense regions the density is always less than the mean density, thus galaxy formation is not possible.

Initially we believed that pancakes are 2-dimensional surfaces as predicted by Zeldovich.<sup>50</sup> To our surprise we did not find evidence for the presence of wall-like structures between voids – *the dominating structural element was a chain (filament) of galaxies and clusters.* The absence of wall-like pancakes and the dominance of filaments was explained theoretically by Bond, Kofman & Pogosyan,<sup>59</sup> through the effect of tidal forces.

The presence of filaments and voids in the galaxy distribution was met with some scepticism. One objection against the new concept was raised by Peebles: the

human brain has a tendency to see regularity (filaments in galaxy distribution) even in the case if the actual distribution is almost random. Zeldovich<sup>58</sup> addressed this problem in his talk during the IAU Symposium and suggested that objective criteria should be used to check this aspect of the galaxy distribution. Together with the Zeldovich team we developed several methods to characterise the filamentary distribution. One of these methods was the multiplicity function of galaxy systems, it is sensitive to the richness of galaxy systems. The other test applied was the connectivity or percolation test, which makes difference between galaxy systems consisting of isolated clusters, clusters connected with filaments, and a random distribution of galaxies.

Applying these tests to real galaxy samples confirmed the presence of galaxy systems of very different richness, and a high connectivity due to galaxy filaments between superclusters. The application of tests to simulated structures showed that the original Zeldovich scenario (where small-scale perturbations were absent), as well as the Peebles scenario, have some problems. The Zeldovich scenario passes the percolation test, but not the multiplicity test – there are no fine structures within superclusters. The Peebles scenario fails both tests, results of these tests were described by Zeldovich, Einasto & Shandarin<sup>60</sup> and Einasto et al.<sup>61</sup>

Difficulties with both scenarios were solved when the Cold Dark Matter model of structure formation was applied, which unites best properties of both the Zeldovich and the Peebles scenarios (Melott et al.,<sup>48</sup> Blumenthal et al.<sup>49</sup>). Galaxies form by clustering and merging of smaller galaxies as suggested by Peebles, but their formation starts in future superclusters, where the density is highest, as it follows from the Zeldovich pancake scenario.

At the time of the Tallinn symposium only relatively small areas of sky were covered by complete magnitude-limited galaxy samples, thus many astronomers were suspicious to the presence of the overall cellular distribution. It was evident that wide-area and deeper flux-limited galaxy redshift surveys are needed. Harvard astronomers made for the whole Northern hemisphere a survey up to limiting magnitude 14.5, later the survey was extended to 15.5 magnitude, CfA1 and CfA2 surveys, respectively. The second CfA surveys shows the filamentary character of the galaxy distribution very clearly, as seen from the first slice of their study by de Lapparent, Geller & Huchra.<sup>62</sup> The presence of the cosmic web was confirmed.

A much deeper redshift survey up to the blue magnitude 19.4 was made using the Anglo-Australian 4-m telescope. This Two degree Field Galaxy Redshift Survey (2dFGRS) covers an equatorial strip in the Northern Galactic hemisphere and a contiguous area in the Southern hemisphere.<sup>63</sup> Over 250 thousand redshifts have been measured. Presently the largest project to map the Universe, the Sloan Digital Sky Survey (SDSS), has been completed by a number of American, Japanese and European universities and observatories.<sup>64</sup> The goal was to map a quarter of the entire sky: to determine positions and photometric data in 5 spectral bands of galaxies and quasars, and redshifts of all galaxies down to red magnitude  $r = 17.7$  (about 1 million galaxies). All 7 data releases have been made public. This has allowed to



map the largest volume of the Universe so far. Fig. 12 shows the luminosity density field of a shell of thickness  $10 h^{-1}$  Mpc at a distance  $d = 240 h^{-1}$  Mpc from us.

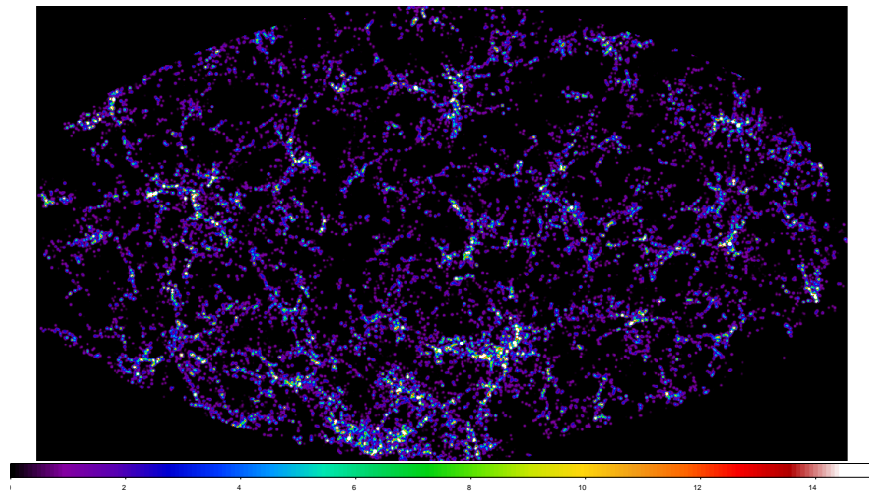


Fig. 12. Sloan Digital Sky Survey, Northern section: a shell of thickness  $10 h^{-1}$  Mpc at a distance  $d = 240 h^{-1}$  Mpc from us, as seen on sky in coordinates  $x = -d \lambda$  and  $y = d \eta \cos \lambda$ , where  $\lambda$  and  $\eta$  are intrinsic SDSS spherical coordinates. Filamentary superclusters of various richness, voids and weak filaments crossing voids are well seen. The rich complex in the lower region is the Great Wall, a complex of several very rich superclusters.

The discovery of the non-baryonic nature of the Dark Matter has resolved the first fundamental problem of the Dark Matter, discussed by Tammann in Tbilisi in 1975. The second problem, the smoothness of the Hubble flow, was explained only recently with the discovery of Dark Energy, previously called also cosmological lambda term. Two teams, led by Riess<sup>65</sup> (High-Z Supernova Search Team) and Perlmutter<sup>66</sup> (Supernova Cosmology Project), initiated programs to detect distant type Ia supernovae in the early stage of their evolution, and to investigate with large telescopes their properties. These supernovae have an almost constant intrinsic brightness. By comparing the luminosities and redshifts of nearby and distant supernovae it is possible to calculate how fast the Universe was expanding at different times. The supernova observations give strong support to the cosmological model with the  $\Lambda$  term.

Studies of the Hubble flow in the nearby space, using observations of type Ia supernovae with the Hubble Space Telescope (HST), were carried out by several groups. The major goal of the study was to determine the value of the Hubble constant. As a by-product also the smoothness of the Hubble flow was investigated. One of these projects was led by Allan Sandage.<sup>67</sup> The analysis confirmed earlier results that the Hubble flow is very quiet over a range of scales from our Local Supercluster to the most distant objects observed. This smoothness in spite of the inhomogeneous local mass distribution requires a special agent. Sandage emphasises

that no viable alternative to Dark Energy is known at present, thus the quietness of the Hubble flow gives strong support for the existence of Dark Energy. This effect has been investigated in detail by Arthur Chernin.<sup>68</sup>

## 6. Conclusions

- The presence of Dark Matter in the Universe and the Cosmic Web were established gradually by astronomers from many centers, in several cases Tartu astronomers have pioneered in these studies.
- Initially the Dark Matter concept had many problems, until its non-baryonic nature and the presence of Dark Energy were found ( $\Lambda$ CDM model). Also the concept of the web-like distribution of galaxies was initially met with scepticism, which disappeared when wide-area and complete redshift surveys were completed.
- The discoveries of Dark Matter and Cosmic Web are connected: Dark Matter as the dominant population in the Universe determines properties of the Web, and the structure of the Web gives information on properties of DM particles.
- In the study of Dark Matter and the structure of the Universe our Tartu team benefited from the earlier experience in Tartu by Öpik, Rootsmäe and Kuzmin, and especially from a close collaboration with the Moscow cosmology team led by Yakov Zeldovich.

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