STRUCTURE AND EVOLUTION OF THE UNIVERSE ON THE GALACTIC AND COSMOLOGICAL SCALES, HIDDEN MASS AND DARK ENERGY: THEORETICAL MODELS AND OBSERVATIONAL RESULTS

Berczik P.P., Vavilova I.B., Zhdanov V.I., Zhuk A.I.,
Karachentseva V.E., Minakov A.A. (posthumously), Novosyadlyj B.S.,
Pavlenko Ya.V., Pelykh V.O., Pilyugin L.S.

ABSTRACT

The presented work is a result of collective achievements of the authors covering a wide range of theoretical and observational problems and making the substantial contribution to the development of the Ukrainian school of extragalactic astronomy and cosmology. For the first time a number of results have been obtained in the development of the Standard cosmological model as well as its extensions using the extra dimensions and scalar fields. New approaches to the detection and investigation of the spatial distribution of matter, the structure and abundance of the galaxies have been proposed. The obtained priority results refer to kinematics, dynamical and chemical evolution of our and other galaxies as well as ultracold stars being an important component of the hidden baryonic matter. The created new galaxy catalogs are widely used for studies of distributions of the visible and hidden mass.

Introduction

During the last decade new astronomical data have changed radically the understanding of the current stage of the cosmological expansion and set new tasks for the fundamental physics. Studies of structure of the Universe indicate that the abundance of the usual baryonic matter (including planets, stars and galaxies; interplanetary and intergalactic gas and dust) does not exceed 5% of the average matter density in the Universe. The main part comes from the so-called “dark energy” (DE, – approximately 73%) and “dark matter” (DM, – approximately 22%). Modern science faces the problems of identification and study of these invisible components of the Universe. Such work is currently rapidly developing worldwide and belongs to the most priority areas of research.

It is well-known that the astronomical research remains the only source of the experimental data confirming the existence of DM and DE. This fact has stimulated the formation of the new scientific branch called the «astroparticle physics», which uses astronomical data for the investigation of the matter microstructure as well as the data on the microstructure for the understanding of evolution of the Universe. Considering just cosmological and astrophysical systems it is possible to obtain the constraints on microscopic DM models and field-theoretical DE models. Not to underestimate the importance of the study of elementary particles in the ground-based laboratories, it should be noted that none of the accelerators could not reconstruct the physical conditions of the early stages of evolution of the Universe. However these conditions and properties of fundamental interactions have affected the characteristics of CMB and the power spectra of the matter density contrast at different scales related to distributions of some classes of astronomical objects as well as the chemical composition of the baryonic matter in galaxies. These data on the structure of the Universe at the galactic and cosmological scales are also the only source of the non-trivial information on DM and DE, thus the development of new astronomical methods for obtaining and

interpretation of these data is quite actual task. Being not easy in itself, it is complicated by the fact that the substantial part of the observations corresponds to the current epoch and should be extrapolated to the earlier ones. So the value of the results on the objects containing the primordial matter (such as G-dwarfs and dwarf irregular galaxies, DM in the halos of galaxies, groups and clusters of galaxies) becomes just higher.

The presented work reflects achievements of authors and their fundamental contribution to these branches of extragalactic astronomy and cosmology. The tasks of this complex research can be divided for convenience into 3 levels corresponding to the spatial and temporal scales of the studied objects, however these levels overlap.

1. At **the global cosmological level** it is necessary to analyze *the generalizations of the Standard cosmological model* and reject the non-viable theories, to develop *the models of DM and DE*.

2. At **extragalactic scales** for the investigations of structure of the Universe *the theoretical predictions of cosmological model with cold dark matter and cosmological constant as well as its generalizations* are needed. On the other hand, this branch needs the detailed analysis of *the modern observations of large-scale structure of the Universe* and the development of *new methods for obtaining the cosmological data*.

3. At **galactic scales** some problems related to *the physical and chemical properties* of galaxies and modeling of their *evolution* appear. This needs the development of the effective methods of obtaining the parameters of particular galactic objects as well as the whole galaxies.

Global models of the structure and evolution of the Universe: theory and observations

In modern physics there exists a precise understanding of the fact that the analysis of the very early, e. g. inflationary, stages of evolution of the Universe as well as the nature of DE and DM requires the substantial changes of the Standard cosmological model. In the authors` works these priority issues have been studied for the models with extra space-time dimensions and additional cosmological fields.

Multidimensional cosmology is the new scientific branch having the fundamental significance not only for cosmology and astrophysics but also for elementary particle physics. Priority results in this field obtained by A. Zhuk have received the wide acceptance. In these works *the new exact solutions for multidimensional cosmological models* in the classical sector have been found, their value is due to the fact that they allow to study in details of the dynamical behavior of internal and external spaces and comparison of this behavior with the observable Universe. The priority results have been obtained in *quantizing of these multidimensional models* and the search for *the new exact solutions of the quantized equations*. The obtained exact solutions were the first known ones for the quantum Wheeler-DeWitt equation in multidimensional cosmology. Another research area corresponds to the fundamental problem of compatibility of multidimensional Kaluza-Klein models with classical gravitational tests. It is determined the physical criteria for viable theories.

In works by B. Novosyadlyj on *the scalar field DE models* for the first time *the parameters of DM have been obtained* from the observational data on Supernovae type Ia, *characteristics* of the large-scale structure and the *CMB anisotropy*. It is shown that *the scalar field as the dynamical DE with variable density and equation of state para-*

meter agrees with the data better than the standard models with cosmological constant; the models without DE are ruled out at the confidence level larger than 99,99%.

The outstanding discoveries in cosmology and astrophysics lead often to critical analysis of basic concepts of the Special and General Relativity (GR). In works by V. Pelykh the new *tensor method of proving the positive energy theorem* in asymptotically flat spaces of GR has been developed and validated. The geometrical nature of the spinor Witten field has been shown, including the case of presence of dark energy. V. Zhdanov has studied problems of the uniqueness of solutions in the *dynamics with finite speed of propagation of interactions* (typical for any relativistic theory), the convergence of iteration procedure has been proved for model equations of motion which proves a validity of standard approximate methods. The conditions of existence of the shock waves in media with general equations of state in sense of Bethe and Weyl in relativistic magnetic hydrodynamics have been proven; these results are of interest for studies of superdense objects in the neighborhood of phase transitions.

Theoretical calculations of large-scale in homogeneity parameters in models with DM and DE

In the authors` articles the important results have been obtained for *the estimation of parameters of cosmological model and power spectrum of primordial density perturbations* comparing the theoretical predictions with observational data on mass function of galaxy clusters, peculiar velocities of galaxies, spatial distribution of galaxies and CMB anisotropy. B. Novosyadlyj in his pioneering works (long before the worldwide acceptance of DE) has shown that the quantitative agreement of theory and observations is reached in models with DM and cosmological constant. Convenient analytic approximations for the computation of the power spectrum in mixed models have been proposed; these have been used intensively by other scientific teams. The upper estimate of neutrino dark matter fraction has been found (< 10% of the total density of the Universe); it has been also found that the upper limit on the rest mass of degenerate active neutrinos is <0.3 eV at the 95% confidence level. The predictions of the models with known abundances of DM, DE and nearly scale-invariant spectrum of primordial perturbations agree with observational data. The authors were one of the first to explain the galaxy large-scale flow on the Great attractor as the result of the large-scale peak of the matter density perturbation, as well as they modeled the influence of such structure on the CMB anisotropy. An important conclusion has been drawn that the tensor mode in realistic models of the early Universe contributes only at the large angular scales (at spherical harmonics <10) and does not exceed 60% of scalar mode contribution. The results of BICEP2, which have been announced at March 2014, confirm the early inflation stage of the Universe expansion, relic gravitational waves and well agrees with our prediction. The authors` results become especially important in the epoch of precision cosmology, in which the development of methods of simultaneous estimation of cosmological parameters from all available data is of importance.

Large-scale matter distributions: methods and analysis of observations

Physical and kinematic properties of matter at scales of groups and clusters of galaxies are among the main sources which give the experimental basis for the cosmological parameters estimation and testing DM and DE models as well as for the cosmological

theories. The authors have analyzed a large number of the observational data; this made the stable foundation for the comparison with theoretical predictions. The results are important for the further studies of DM and estimation of parameters of the large-scale inhomogeneity; they have been used and are being applied widely in the international programs for the Local Universe cartography.

The unique "material" for such study comes from *the dwarf galaxies with low surface brightness* (LSBD), which is the most numerous population of galaxies in the Universe. They are regarded as the perfect laboratories for investigation of the star formation processes in galaxies and dark matter problems. Dwarf galaxies are also important as the "test particles" for the study of structure of the Universe at few Mpc scales, as well as origin and evolution of galaxies. The works on search and study of dwarf galaxies with low and extremely low surface brightness were begun by V. Karachentseva in 1968. As a result of search for dwarf galaxies in the First Palomar Sky Survey approximately 400 objects have been found, the majority of which has not been catalogued before. On the basis of the original results and critical analysis of the observable data, which were known till 1986, the reference all-sky "*Catalog of low surface brightness dwarf galaxies"* has been created as well as the morphological classification scheme for DGLSB has been developed.

I. Vavilova proposed the cluster analysis for this catalog, which allowed to obtain for the first time the quantitative characteristics and to show the principal difference in distributions of these galaxies with different types of population at the scales of the Virgo and Fornax galaxy clusters and in the volume of the Local Supercluster. Independent searches by V. Karachentseva with co-authors allowed to find 327 new dwarf members in the POSS-II, ESO/SERC and SERC/EJ sky surveys; the observations with large radio telescopes have been made in the line HI 21 cm for all candidates, the radial velocities, line widths and fluxes have been obtained. These results served as a basis for the international projects using the Hubble Space Telescope, in which, with participation by V. Karachentseva, the observations of LSBDs at distances up to 10 Mpc have been made and the fundamental result – *the 3D map of galaxy distribution in Local Volume* – has been obtained.

V. Karachentseva in co-authorship created "A Catalog of Neighboring Galaxies" (CNG) on the basis of original observations and literature data that includes all the sky and contains 451 Local Volume Galaxies. These data are principal for the selection of cosmological models and are widely used in the study of physical properties of galaxies. The first and widely accepted as the most representative and complete "Catalog of Isolated Galaxies" (CIG) has been created by V. Karachentseva based on the original selection criterion. For the first time the part of isolated galaxies in a magnitude-limited catalog has been found to be approximately 4%, which puts the constraints on the processes of large-scale structure formation. The isolated galaxies serve as some type of standard objects as they have not experienced the dynamical influence of their neighbors during the last 1-2 billion years, so their properties are caused by their own evolutionary processes. Using the material of infrared survey 2MASS the new catalog of isolated galaxies, 2MIG, containing 3227 objects, has been created. It is worth noting that today there are only 3 full-sky samples of isolated galaxies: CNG (up to 10 Mpc), new LOG (within 45 Mpc) and 2MIG (within 80 Mpc) catalogs.

The authors have developed new methods for study of the large-scale structure and clustering the extragalactic objects using the Voronoi tessellation, fractal and wavelet analysis. The method of Voronoi tessellation employed in the works by I. Vavilova allowed finding the dependences between the morphological type, color index and other parameters of galaxies belonging to the groups of different multiplicity. The obtained "mass-to-luminosity" relations for galaxies allowed to estimate the DM abundance in the small groups (from 20 to 50 M_{Sun}/L_{Sun} depending on the contents of the group) and to draw the conclusion that in the groups, in which the galaxies of late types dominate, DM is concentrated in the group halo. The new method of estimation of clustering the distant galaxies which accounts the observational selection effects has been developed; this method appeared to be efficient even for the heterogeneous catalogs existing before the SDSS and 2dF large surveys. Later, this method has been modified and applied to different releases of SDSS; as a result the parameters of correlation functions of quasars have been obtained for scales from 2 to 50 Mpc.

The gravitational lensing is one of the few important tools giving information on the structure of most distant objects and mass distributions in the Universe. A. Minakov was one of the founders of this scientific field in Ukraine: his first work (1975, with co-authors) has been 20 years ahead of similar works in the world scientific community. The world first monograph on gravitational lensing (P.V. Bliokh, A.A. Minakov) was also pioneering. This and next research created the fundamentals of the theory of gravitational lensing, based on experience of the Kharkiv school in radio physics. The developed approaches allowed the authors to obtain a number of important results, e. g. to investigate the critical and caustic curves of the gravitational lens system (GLS), to analyze brightness variations of the lensed images at critical values of the surface mass density of the microlens-galaxy. A new effect related to lensing of the variable in time source has been predicted and thoroughly studied. Application of the theoretical results to the analysis and interpretation of GLS observations allowed to estimate the relative dark matter abundance in the total mass of the deflector of GLS Q2237+0305. For this GLS the properties of the total X-spectrum have also been obtained. The upper estimate for the mass of possible dark matter substructure in GLS PG1115+530 is also new.

In works by V. Zhdanov on astrometric microlensing it has been shown for the first time that in the extragalactic GLS the motions of the microlensed quasars images could be comparable with proper motions of quasars. In case of the stochastic thin system of microlenses the analytic expressions for the probability distribution of the images motion have been found for the first time; the simple final expression allows to consider this as a textbook result. In the authors` works it has been pointed out for the first time that the collective motion of the stars induces (besides the random motion) the additional motion of image of the distant source; this is of principal importance for the astrometric reference frame based on distant sources. Also for the first time, simultaneously with other authors, it has been shown that the trajectory of an image centroid changes qualitatively in case of extended source. This opens additional possibilities to study the source structure and provide that a sufficient precision of astrometric observations will be obtained.

Chemical evolution of galaxies: new methods and results

It is known that the primordial (pregalactic) abundances of the some chemical elements (deuterium, helium) are used in determination of the fraction of non-baryonic matter. The most precise estimates of the fraction of the non-baryonic component (DM) have been obtained in this manner. Thus, the abundance determinations are important for many reasons, in particular investigations related indirectly to the DM study. The study of the chemical composition of objects in galaxies allows drawing conclusions regarding the formation and evolution of galaxies. The works by L. Pilyugin are devoted to this topic, the new methods for the abundance determination in galaxies and new models of chemical evolution of spiral and irregular galaxies have been developed there. In these works the new method for determination of the chemical composition (the abundances of oxygen and other elements) in the regions of ionized hydrogen (HII regions) has been proposed. It has been shown that the precision of determination of oxygen abundance through the new method is not lower than that through the classical one, but it has the advantage of being based only on intensities of strong nebular lines, while the classical methods require the measurement of the very weak auroral lines. The oxygen abundance in a sample of the giant spiral galaxies has been redetermined using the new method that allowed concluding that the oxygen abundance in the Universe is 2-3 times lower than it had been estimated before.

It has been shown that the canonical model of the chemical evolution of the Galaxy cannot reproduce all the observational data. The multifragment model of the chemical evolution of the Galaxy has been proposed, which allows explaining consistently the observational data for the halo and disc of the Galaxy. The concept of the enriched galactic winds has been developed. It has been shown that the effects of influence of ordinary galactic winds and enriched galactic winds on the chemical evolution of galaxies are quite different. The models of the galaxy chemical evolution with the enriched galactic winds reproduce the “luminosity-metallicity” relation for galaxies while the models with ordinary galactic winds do not. The timescale for the nitrogen synthesis has been established. The nitrogen abundance in a galaxy has been found to depend on the star formation rate. Ratio of nitrogen to oxygen abundances is shown to be an indicator of time from the moment of formation of the main part of stars in the galaxy.

Numerical simulation of the complex evolution of galactic systems

Methods of numerical simulation become important in the current ab initio calculations of evolution of the large-scale structure of the Universe and its elements, which give a possibility to test fundamental cosmological postulates. The modern computational facilities allow not only to process effectively large arrays of observational data but also to simulate complex astrophysical systems with unachievable before numerical resolution. In this case the development of effective software allowing the maximal usage of the available hardware becomes exceptionally important.

In works by P. Berczik the analysis of 3D-gasodynamical collapse of triaxial protogalactic fragments has been fulfilled for the first time by the smoothed particle hydrodynamics (SPH). The developed numerical models allow describing the initial process of galaxy structures formation in the most general way. It has been shown that the developed method allows taking into account self-consistently the processes of

formation of the star component nearly independently of the initial split of the gaseous component into fragments (the number of SPH-particles). Also it has been shown for the first time that this algorithm gives the possibility to interpret the results obtained with quite moderate numbers of initial SPH-particles with sufficient precision and to use them for the whole galaxy containing much more gaseous fragments than it is possible to use in simulations. For the first time the usage of the "energetic criterion" of the star formation effectiveness has allowed to construct the adequate model for *the quantitative analysis of the chemodynamical evolution of our Galaxy*. The proposed gas-dynamical code has allowed to describe self-consistently both global and local (in the Solar neighborhood), dynamical and chemical evolution of the disc galaxy (with general parameters close to our Galaxy). The proposed by P. Berczik numerical model has described for the first time in the framework of general self-consistent model the global dynamical and chemical properties of the disc. The complex consideration of the gas-dynamical evolution and matter exchange between the stars and gaseous phase allowed *to propose for the first time the adequate mechanism of solution of the so-called "G-dwarfs problem"* in the Solar neighborhood. For the first time it has been shown that different gaseous components of galaxies have different history of the heavy elements enrichment; the comparison with modern observations of dwarf galaxies has been made.

Using the recent computational technology (GPU – Graphics Processing Units) the exceptional works (by number of particles and time interval of integration) on the high-precision dynamical simulation of evolution of the galactic center, including the super-massive black hole motion, have been done for the first time. These works have given the possibility to refine significantly the early analytic calculations of the "gravitational Brownian motion" of the black hole in the distribution of the stars field and to obtain the estimates of the mass of the central invisible body that are in the good agreement with direct measurements. For the first time it has been shown that the characteristic time of the black holes merging in the center of the galaxies, for the typical parameters of black holes masses and angular moments of orbits, is approximately 1 billion years. For the first time the high-precision numerical integration of the evolution of the binary black hole in the center of the galaxy has been made using the massive-parallel phi-GRAPE+GPU code. It has been shown that independently of the number of the "stellar" particles (N varies from 25000 to 1000000) the temporal derivative of the quantity inverse to the large semi-axis of the binary black hole (so-called "hardening rate") does not depend on the number of stars.

For the first time *the calculations of motion of the stellar clusters in the gravitational complex potential of the Galactic disc* have been made with highest resolution ("one star — one particle"), they have shown that the visible ellipticities of observable stellar clusters are in good agreement with numerical simulations. In these works for the first time the dynamical evolution and energetic of the loss of stars by clusters caused by the tidal forces in the galactic disc are studied in detail.

Physics and evolution of the low mass stars

The low mass stars are the important part of the hidden baryonic matter. Let us remind that at the end of the previous century one of the priority problems was the role of compact objects (MACHO) in the structure of the galactic halo, the candidates for this role are low mass cold stars, e. g. brown dwarfs. Later it was found that these objects do

not make the main mass contribution to the halo, despite of they are the most numerous stars in the Galaxy.

Ya. Pavlenko carried out pioneering works to investigate the formation of the spectra of ultracold dwarfs and brown dwarfs. He showed in 1995 the possibility of realization of the so-called "Lithium test" for the determination of the subsample of brown dwarfs among the low mass stars of the Galaxy disc. The direct spectral observations of the resonance region of the Lithium doublet confirmed his predictions and showed for the first time the presence of the lithium in the atmosphere of the first discovered brown dwarf Teide1, despite of the presence of the strong absorption by TiO absorption bands. In the works during 1997-2008, the new and original procedure of calculation of the spectra of stars of late spectral classes and brown dwarfs was developed and realized. It allowed determining the Lithium abundance in the atmospheres of Teide1 and of a number of young brown dwarfs from the open clusters. The proposed in his works concept of the "pseudo equivalent widths" is still successfully applied now. The investigation of the processes of formation of spectra of dwarfs class L showed that it is possible to use the "Lithium test" for determination of the substellar nature of low mass L-dwarfs. Furthermore, the method of calculation of the Natrium and Kalium superstrong absorption resonance lines profiles dominating in the optical spectral range of L-dwarfs has been developed. In 2007 the new version of the "Deuterium test" was proposed. Pavlenko Ya. with scientists from the IAC (Spain) have conducted the theoretical investigation of the formation of Lithium lines in the atmospheres of young low mass stars of the Galaxy disc with account of the deviations from the local thermodynamical equilibrium. The obtained results on the Lithium abundance in atmospheres of classical and weak T Tau stars are classical and remain actual up to now. In another series of works the nature of recurrent Novae and objects with ultrafast evolution was investigated and the evolutionary characteristics for a number of such objects were obtained for the first time.

New priority results obtained since previous presentation of the work

For the first time, we have shown for multidimensional Kaluza-Klein models that the variation of the total volume of the internal space generates the fifth force that results in violation of the gravitational interaction. A completely new result is the proof of the absence of the Kaluza-Klein particles in the considered models. It was established that the best fitting value of the equation of state parameter of the scalar field models of DE is in the phantom domain; if it will be confirmed in subsequent observations it will change significantly the current understanding of the cosmological evolution.

Parameters of the Tully-Fisher correlations are obtained for isolated galaxies of the 2MIG-catalog, having importance for understanding of the LSS evolution. The contribution of pairs, groups and clusters of galaxies in the Local Universe and their characteristics are estimated, that can be used for comparison of different scenario of the LSS origin. The multiwave properties of the isolated 2MIG galaxies with active nuclei were analyzed and, for the first time, the masses of black holes in their centers were obtained. These values are to be systematically lower than the masses of black holes of AGNs in galaxy groups and clusters. The method is generalized (that has been worked out by the authors earlier) to study the gravitational lens mapping in a vicinity of stable singularities including the case of DM presence.

A new method is worked out for determination of the oxygen abundance in regions of ionized hydrogen HII, where there are no measurements of the line of ionized oxygen [OII] 3727. This makes it possible to study a chemical composition of a large number of HII regions in a nearby galaxies using spectra, which have [OII] 3727 line beyond observed spectral interval. Chemical compositions of Milky Way disk stars is investigated, primarily for stars with planetary systems.

In 2012 the authors published 44 papers in the refereed journals, 5 chapters in the collective monographs and 4 in collections of works. Three candidate dissertations (PhD theses) were defended under supervision by A. Zhuk, L.Pilyugin and V. Tsvetkova (the first supervisor – A. Minakov). The results of our work are summed up in the monograph "Dark Energy and Dark Matter of the Universe", Ed. Shulga V.M., in 3 volumes; Vol. 1 is already published: "Dark Energy: Observational Evidence and Theoretical models" (Novosyadlyj B.S., Pelykh V.I., Shtanov Yu.V., and Zhuk A.I. Ed. V.M. Shulga. – K.: Akademperiodyka, 2013, 380 pp.; Vol. 2 "Dark Matter: Astrophysical Aspects of Problem" (Shulga V.M., Zhdanov V.I., Berczik P.P., Pavlenko E.P., Pavlenko Ya.V., Pilyugin L.S., and Tsvetkova V.S.) is in press. Two more monographs are published: "The Ionized Gas in Galaxies: Physical State and Chemical Composition" (Pilyugin L.S. – K.: Naukova dumka, 2013, 288 pp.); "General Relativity: Horizons for Tests (Y.S. Yatskiv, A.N. Alexandrov, I.B. Vavilova, V.I. Zhdanov, A.I. Zhuk, Yu. N. Kudrya, S.L. Parnovsky, E.V. Fedorova, and S.V. Khmil. – Kyiv: MAO NAS of Ukraine, 2013. – 264 pp.). In 2013 the authors published 48 papers related to the given work in the refereed journals.

Conclusions

The obtained results advance significantly our knowledge of the structure and evolution of the Universe on galactic and cosmological scales, create theoretical and experimental basis for understanding of the nature of dark matter and dark energy. The main priority achievements of the authors are as follows:

- *The new theoretical models of global structure of the Universe with extra dimensions have been created, the new classical and quantum solutions have been found, the observational constraints on the parameters of these models have been set; the multidimensional models of DM and DE have been proposed.*
- *The cosmological models with the scalar field as the dynamical DE have been developed and for the first time the parameters of DM have been constrained using the observational data on the Supernovae type Ia, large-scale structure of the Universe and CMB anisotropy. On this basis long before the publication of the well-known results on acceleration of the cosmological expansion the conclusion about the non-zero value of cosmological constant has been obtained.*
- *The principal questions of the General Relativity important for the validation of the basic principles of the standard model have been elaborated.*
- *The original galaxy (dwarf, isolated etc.) catalogs have been created, on this basis the qualitative and quantitative characteristics of the local matter inhomogeneity at the scales up to 10 Mpc have been found. The mentioned catalogs served as the foundation of the international observational programs using the Hubble Space Telescope, they are also widely used by other authors in their research.*

- *The new approaches to the analysis of clustering of the extragalactic objects allowed obtaining the reliable data on the DM abundance in the groups of galaxies.*
- *The created consistent theoretical description of the gravitational lensing phenomenon was one of the first in the world; the predicted new photometric and astrometric effects serve as the basis for estimates of the mass distribution in the gravitational lens systems.*
- *The new methods to the determination of the chemical composition of galaxies have been proposed; it has been shown that the Oxygen abundance in the Universe is 2-3 times lower than it has been considered before.*
- *For the first time the multifragment model of the chemical evolution of the Galaxy has been constructed, it has overcome the non-consistencies of the previous (canonical) one.*
- *For the first time the self-consistent numerical model of the chemodynamical evolution of galaxy has been developed; the outstanding by the resolution numerical simulations of the evolution of galactic center have been made.*
- *The new method of the calculations of spectra of the stars of the late spectral classes and brown dwarfs has been developed; the priority investigation of the formation of Lithium lines in atmospheres of young low mass stars forming the most numerous population of compact objects in the Galaxy has been made.*

The results of our study **have not only scientific but the large world view importance** since they have to do with the most fundamental questions at the frontier of the modern physical theories related to the existence and origin of the Universe. First and foremost **they are important for the astronomy (cosmology, cosmogony)**; they are also of significant interest for solving **the problem of non-baryonic (dark) matter and dark energy**, which is the fundamental problem of the whole modern natural science since these components dominate in our Universe. The developed generalized cosmological models are especially interesting as the testing area **for the modern theories of fundamental interactions**. The presented work makes a substantial contribution to the development of the Ukrainian school of extragalactic astronomy and cosmology, which represents worthily the Ukrainian science worldwide. The authors` study has been and is supported repeatedly by the international programs, the programs of the NAS of Ukraine, and the projects of the State Fund for Fundamental Researches.

Thus, the authors` team has made the significant contribution to the formation of modern notions of structure and evolution of the Universe. This is indicated by more 1000 publications during 40-year period; from these the presented work includes 471 publications and 4 databases. The publication list contains 5 monographs, 25 author's chapters in the collective monographs, 419 refereed articles, and 13 works in refereed proceedings. The authors use actively their results in training of young researchers; the published 9 textbooks are used in the system of university education. The high level of research and international authority of the authors` team is confirmed by the publications in leading journals with the highest impact factors. The number of citations in the SAO/NASA/ADS database to the authors` works exceeds 9500. The Hirsh index (SAO/NASA ADS) $h = 44$. The work resulted also in the defenses of 9 Dr. Sci. and 25 Cand. Sci. (Ph.D.) theses.