Two fields of astrophysical studies: Fundamental constants and neutron stars

D. A. Varshalovich, D. G. Yakovlev, A. Y. Potekhin and A. V. Ivanchik

There have been various fields of studies in the Department of Theoretical Astrophysics during the past decades. For this review, we have selected just two of them: fundamental constants and neutron stars. Each of these fields of study reveals a deep connection between the fundamental theoretical physics and the astrophysics.

Contemporary endeavours to build the Grand Unification Theory (GUT) have led to the prediction that the fundamental physical constants should have changed during the history of the Universe (some 10 billion years). To check this exciting prediction, one should "measure" the constants in the early cosmological epochs. This can be done only by astrophysical methods. The first part of the present review, written by D.A.V., A.Y.P. and A.V.I., describes the work in this direction.

The second part, written by D.G.Y., is devoted to not less exciting circle of problems, which may look diverse but all are related to some of the most remarkable astronomical objects: the neutron stars. These stars are characterized by extreme conditions: superhigh densities, electromagnetic fields, gravitational and centrifugal accelerations, which are not available in the terrestrial laboratory. Behaviour of matter in such conditions presents a challenge to the contemporary physics.

1 Measuring the fundamental constants in the early Universe

1.1 Introduction

Every physical theory uses some parameters determined either from experiment or from a more fundamental theory. The most fundamental parameters are called fundamental physical constants (e.g., the electron charge e, the Planck constant $\hbar$, the speed of light c, the masses of elementary particles, etc.). However a numerical value of any dimensional parameter depends on arbitrary choice of physical units. Only dimensionless combinations are truly fundamental, such as the fine-structure constant $\alpha = e^2/(\hbar c)$, the proton-to-electron mass ratio $\mu = m_\mathrm{p}/m_\mathrm{e}$, etc. The current theories cannot derive their numerical values. Hopefully these values will be provided by GUT, which has not been created yet. Many attempts to construct the GUT have led to numerous theoretical models, claiming that the fundamental constants are, in fact, not true constants but slowly varying functions of time[1]. Clearly, a discovery of these variations would be a great step in our understanding of Nature. Even a reliable upper bound on a possible variation rate of a fundamental constant presents a valuable tool for selecting viable GUT models.

Historically, a hypothesis that the fundamental constants may depend on the *cosmological time t* (that is the age of the Universe) was first discussed by Milne [1] and Dirac [2]. The latter author proposed his famous "large-number hypothesis" and suggested that the gravitational constant was directly proportional to t. Teller [3] showed, however, that such variation was inconsistent with geological and paleontological findings. Later the

[1] The prediction of the theory that the fundamental constants depend on the energy of interaction has been confirmed in experiment. In this paper, we consider only the space-time variability of their low-energy limits.

variability of fundamental constants was analyzed, using different arguments, by such distinguished physicists as Gamow [4], Dyson [5] and others. The interest in the problem has been revived due to recent major achievements in GUT and superstring models (e.g., [6]).

Presently, the fundamental constants are being measured with a relative error of $\sim 10^{-8}$. These measurements obviously rule out considerable variations of the constants on a short time scale, but do not exclude their changes over the entire lifetime of the Universe, $\sim 1.5 \times 10^{10}$ years. Moreover, one cannot rule out the possibility that the constants differ in widely separated regions of the Universe; this could be disproved only by experiments and observations.

It is extremely difficult to increase the accuracy of the present-day experiments and trace possible variation of a fundamental constant during the entire history of the Universe. Fortunately, Nature has provided us with a tool for direct measuring the physical constants in the early epochs. This tool is based on observations of quasars, the most powerful sources of radiation. Many quasars belong to most distant objects we can observe. Light from the distant quasars travels to us about 10^{10} years. This means that the quasar spectra registered now were formed $\sim 10^{10}$ years ago. Because of the expansion of the Universe, distant objects recede from us at a great speed. As a result, the wavelengths of the lines observed in spectra of these objects ($\lambda_{\rm obs}$) increase compared to their laboratory values ($\lambda_{\rm lab}$) in proportion $\lambda_{\rm obs} = \lambda_{\rm lab}(1+z)$, where the *cosmological redshift* z can be used to determine the age of the Universe at the line-formation epoch. In some cases, the redshift is as high as $z \sim 3{-}5$, so that the intrinsically far-ultraviolet lines are registered in the visible range. The examples are demonstrated in Fig. 1. Analysing these spectra we, like a time-machine, may study the epoch when the Universe was several times younger than now.

Here we review briefly the studies of the space-time variability of the fine-structure constant α and the proton-to-electron mass ratio μ. The studies are based on the quasar spectra analyses carried out in the Department of Theoretical Astrophysics of the Ioffe Physico-Technical Institute. This activity has been reviewed in detail in [7, 8].

1.2 Fine-structure constant

The name of the fine-structure constant α was introduced by Sommerfeld in 1916 because the constant defined the fine splitting of atomic energy levels. Now we know that α is the fundamentally parameter in quantum electrodynamics.

The strongest bound on the possible time-variation rate of α was derived in 1976 by Shlyakhter [9], then at the Leningrad Nuclear Physics Institute, and recently, from a more detailed analysis, by Damour and Dyson [10], who obtained $|\dot{\alpha}/\alpha| < 0.7 \times 10^{-16}\,\mathrm{yr}^{-1}$, The analysis was based on measurements of isotope ratios in the Oklo site in Gabon, where a unique natural uranium nuclear fission reactor had operated 1.8 billion years ago. The isotope ratios of samarium produced in this reactor by the neutron capture reaction $^{149}\mathrm{Sm}+n \rightarrow ^{150}\mathrm{Sm}+\gamma$ would be completely different, if the energy of the nuclear resonance responsible for this capture were shifted at least by 0.1 eV.

Another strong bound, $|\dot{\alpha}/\alpha| < 5 \times 10^{-15}\,\mathrm{yr}^{-1}$, was obtained by Dyson [5] from an isotopic analysis of natural radioactive decay products in meteorites.

A weak point of these tests is their dependence on the model of the phenomenon, fairly complex, involving many physical effects. In addition, the tests are associated with the Solar system. They cannot be extended to distant space regions and to the early Universe: the law of possible space-time variation of α is unknown *a priory*. It is the extragalactic

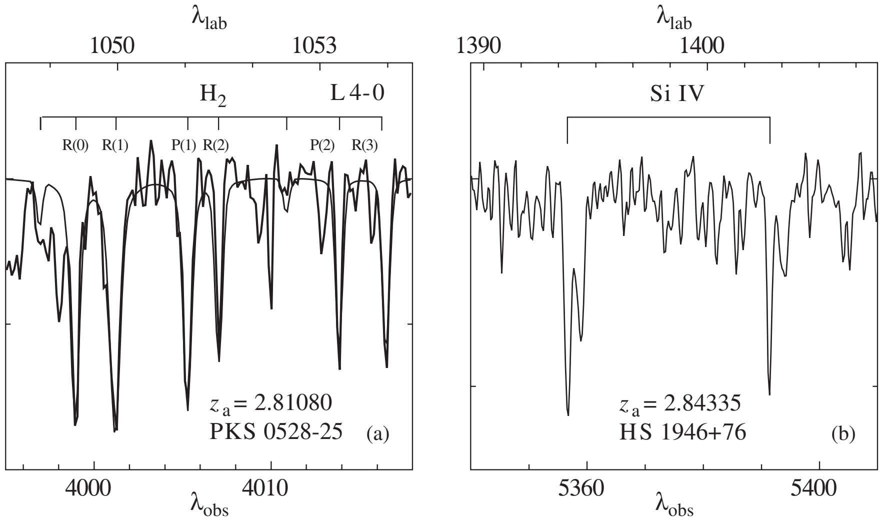

Figure 1: Portions of quasar spectra which show the absorption lines of H_2 and Si IV with large redshifts, $z = (\lambda_{\rm obs} - \lambda_{\rm lab})/\lambda_{\rm lab} \approx 2.8$. The lower horizontal axis gives the wavelengths in the observer's frame ($\lambda_{\rm obs}$) and the upper axis gives the wavelengths in the quasar's frame $\lambda_{\rm lab}$ (in Å). (a) The spectrum (thin line) of the quasar PKS 0528–250, obtained with the 4-meter CTIO telescope (Chile), containing H_2 lines which belong to the L 1–4 branch of the spectrum; thick line plots the spectral fit. (b) The spectrum of the quasar HS 1946+76, obtained with the 6-meter SAO telescope (Russia), containing Si IV doublet lines which correspond to the $^2S_{1/2} \to ^2P_{3/2}$ and $^2S_{1/2} \to ^2P_{1/2}$ transitions.

astronomy that allows us to study these remote regions of spacetime.

To find out whether α changed over the cosmological time, we have studied the fine splitting of the doublet lines of Si IV, C IV, Mg II and other ions, observed in the spectra of distant quasars. According to quantum electrodynamics, the relative splitting of these lines $\delta\lambda/\lambda$ is proportional to α^2 (neglecting very small corrections). Consequently, if α changed with time, then $\delta\lambda/\lambda$ would depend on the cosmological redshift z. This method of measuring α in distant regions of the Universe had been first suggested by Savedoff [11] and was used later by other authors. For instance, Wolfe *et al.* [12] derived an estimate $|\dot{\alpha}/\alpha| < 4 \times 10^{-12}\ \mathrm{yr}^{-1}$ from an observation of the Mg II absorption doublet at $z = 0.524$.

Many high-quality quasar spectra measured in the last two decades have enabled us to significantly increase the accuracy of determination of $\delta\lambda/\lambda$ at large z. The first estimates [13] indicated that α might be changing at the fractional rate $\sim 3 \times 10^{-12}\ \mathrm{yr}^{-1}$ at the 3σ confidence level. This exciting result prompted us to undertake a more thorough study.

At the first stage of our work, we reanalyzed all the published data on the fine-splitting doublet lines observed in quasar spectra. We considered a total of about 1500 pairs of doublet lines with redshifts between 0.2 and 3.7 and compiled a catalog of the wavelengths [14]. An analysis revealed no statistically significant deviation of the ratio $\delta\lambda/\lambda$ from the present value. The wealth of observational material collected in our catalog allowed us to study whether α is different in causally disconnected regions of the Universe. Many regions of formation of the spectral lines, observed at large redshifts in different directions in the sky, had been causally disconnected at the epochs of line formation. Thus, no information could have been exchanged between these regions of the Universe and, in principle, the fundamental constants could be different there. However, a weak dependence of the fine doublet splitting on the direction in the sky found in [7] lies within the 3σ relative error $|\Delta\alpha/\alpha| < 3 \times 10^{-4}$.

Using these results, we optimized the strategy of studying the time-dependence of α. At the second stage of the project [15], we realized a special program of spectroscopic observations of several quasars with the 6-m telescope of the Special Astrophysical Observatory (SAO) of the Russian Academy of Sciences. Our aim was to achieve the highest possible accuracy of the fine-splitting measurements at large redshifts. An example of the spectra observed is shown in Fig. 1. As a result, we obtained a new constraint on the possible deviation of the fine-structure constant at $z = 2.8$–3.1 from its present ($z = 0$) value: $|\Delta\alpha/\alpha| < 1.6 \times 10^{-4}$. The corresponding upper limit of the α variation rate averaged over $\sim 10^{10}$ yr is $|\dot{\alpha}/\alpha| < 2 \times 10^{-14}\ \mathrm{yr}^{-1}$. This constraint is much more stringent than those obtained from previous astronomical observations.

According to our analysis, some theoretical models are inconsistent with observations [14, 7, 15]. For example, a power law $\alpha \propto t^n$ could be reconciled with observations if only $n < 10^{-4}$. This inequality eliminates a broad class of models. In particular, it is in conflict with the Gamow's hypothesis [4] that $n = 1$ and with the theoretical laws with $n = 1$, $-1/4$, and $-4/3$ published by various authors in 1980s. Moreover, the Teller–Dyson's hypothesis on the logarithmic dependence of α on t [3, 5] has also been shown to be inconsistent with observations.

1.3 Proton-to-electron mass ratio

The dimensionless constant $\mu = m_{\mathrm{p}}/m_{\mathrm{e}}$ approximately equals the ratio of the constants of strong interaction $g^2/(\hbar c) \sim 14$ and electromagnetic interaction $\alpha \approx 1/137.036$, where g is the effective coupling constant calculated from the amplitude of nucleon-π-meson scattering.

In order to check the cosmological variability of μ we have used high-redshift absorption lines of molecular hydrogen H_2 in the spectrum of the quasar PKS 0528–250. This is the first (and, in a sense, unique) high-redshift system of H_2 absorption lines discovered in 1985 [16][2]. It was the discovery of a new class of the extragalactic objects: discrete clouds of molecular hydrogen with large cosmological redshifts. A study of these objects yields information of paramount importance on the physical conditions $\sim 10^{10}$ years ago, particularly, on variability of the fundamental constants.

It is important that the electronic, vibrational and rotational energies of a molecule depend on its reduced mass in different ways. Comparing ratios of wavelengths λ_i of various H_2 electron-vibration-rotational lines in a quasar spectrum at some redshift z and in laboratory (at $z = 0$), we can trace variation of μ. The method had been used previously by Foltz *et al.* [17], whose analysis was corrected later in our papers [18, 7, 19]. In the latter papers, we calculated the sensitivity coefficients K_i of the wavelengths λ_i with respect to possible variation of μ and applied a linear regression analysis to the measured redshifts of individual lines z_i as function of K_i. If the proton mass in the epoch of line formation were different from the present value, the measured z_i and K_i values would

[2] For this work, Levshakov and Varshalovich were awarded with the Belopolsky Prize of the Russian Academy of Sciences in 1990.

correlate. However, no such correlation was found within the statistical errors, and we obtained the upper limit on the deviation of μ at $z = 2.811$ (i.e., $\sim 10-12$ billion years ago) from the present value: $|\Delta\mu/\mu| < 0.002$.

We have made even more refined analysis using the modern high-resolution spectrum of the same object obtained by Lanzetta *et al.*. It has enabled us to identify several tens of the H_2 lines; a portion of the spectrum is shown in Fig. 1. From this spectrum we have obtained [20] the restriction: $\Delta\mu/\mu = (-1.15 \pm 0.76) \times 10^{-4}$ at $z = 2.8108$. It corresponds approximately to $|\dot{\mu}/\mu| < 2 \times 10^{-14}\ \mathrm{yr}^{-1}$.

1.4 Conclusions

We have demonstrated how the extragalactic astronomy provides an insight into what the Universe had looked like at early cosmological epochs and in distant regions of space. We have given only two examples, concerning the bounds on possible variation rates of the fine-structure constant α and the proton-to-electron mass ratio μ. The extragalactic astronomy can also give the bounds on other fundamental constants or their combinations. For example, we have shown [7, 8, 19] that not only α and μ but also the ratio of the atomic mass unit to m_e did not change in $\sim 10^{10}$ years by more than a few parts in 10^4. This means that the coupling constants of electromagnetic and strong interactions did not change to a high accuracy. Moreover, they were the same in causally disconnected regions of the Universe.

The derived constraints give effective criteria for selecting theoretical models of elementary interactions which predict variations of the physical constants over the cosmological time scale. In particular, we were the first who showed that the Teller–Dyson's hypothesis on the logarithmic time-dependence of the fine-structure constant was incompatible with observational data.

The work was supported by the RBRF (grants 93–02–02958 and 96–02–16849), by ISF (grant NUO–300), and by the State Programme "Fundamental Metrology". The results were awarded with the First Scientific Premium of the Ioffe Physico-Technical Institute in 1993 and the Grand Premium of the International Academic Publishing Company "Nauka" in 1996.

2 Neutron stars

"Neutron stars are superstars", David Pines once said. And right he was. These tiny stars (of radius $\sim$ 10 km and mass $\sim 1.4\,M_\odot$) are the champions among the stars. They contain superdense matter, show superfast rotation, have superstrong magnetic fields, operate as superpowerful accelerators of superenergetic particles. They entertain astronomers behaving as radio pulsars, X-ray pulsars, X-ray bursters, soft gamma repeaters, and the sources of quasiperiodic X-ray oscillations. Their birth in supernova explosions produces strong neutrino outbursts (detected once from the supernova 1987A). Hopefully, they are the best emitters of gravitational waves.

Here is a history of the neutron-star physics in Theoretical Astrophysics Department of Ioffe Institute from its beginning till February 1998. The first article [21] was written by Yu. N. Gnedin, A. Z. Dolginov, and A. I. Tsygan in 1969, two years after the discovery of pulsars, to model radiation formation in the X-ray source Sco-X-1. The history involves about 250 articles in the refereed journals and conference proceedings (about 50 written before 1980, about 70 from 1980 till 1989, and about 130 later). Their subject is mainly theory of all corners of neutron stars and nearby space related to observations. The most enthusiastic patriarchs were Yu. N. Gnedin (left Dept. in 1984) and A. I. Tsygan. The second generation started working later: N. A. Silant'ev — since 1965 (left in 1985), G. G. Pavlov, A. D. Kaminker, Yu. A. Shibanov — since 1967 (G. G. Pavlov is on leave of absence since 1992; Yu. A. Shibanov is formally in Department of Applied Mathematics and Mathematical Physics, but he is so close to us that we treat him as our dearest colleague); D. G. Yakovlev — since 1971; I. G. Mitrofanov — since 1972 (left in 1981), V. A. Urpin — since 1973 (on leave since 1996). A. G. Muslimov was employed in 1980, converted into the neutron star physics in 1984 and left in 1992. The next generation came in the middle of 1980s: V. G. Bezchastnov in 1986, D. A. Shalybkov in 1989, A. Y. Potekhin and K. P. Levenfish in 1992, V. D. Pal'shin and D. Y. Konenkov in 1995, and D. A. Baiko in 1996. V. E. Zavlin was a PhD student here form 1989 to 1993, and P. G. Mamradze, now a high-rank official in Republic of Georgia, worked here from 1990 till 1992 on his neutron-star PhD. We organized four neutron-star workshops in Leningrad/St. Petersburg in 1988, 1992, 1995 and 1997. You can find our neutron-star information in Internet (`http://www.ioffe.rssi.ru/astro/NSG/`). Our activity is summarized in four sections.

2.1 Radiation from neutron stars

The neutron stars are surrounded by atmospheres, where their radiation is formed. You cannot interpret the radiation without atmospheric models. You cannot borrow the models from other stars which are not superstars. New general theory of the radiative transfer in anisotropic media was developed mainly by the efforts of Gnedin, Pavlov, Silant'ev, and Dolginov (Dept. head till 1986) in 1970s. Basic formulation of the radiative transfer problem in a strongly magnetized plasma [22] has become the foundation of the new field – the radiative transfer in magnetized compact objects. The results were summarized in a monograph [23], and its authors received a prestigious Belopolsky Prize in Russia in 1987.

The electron cyclotron lines in the spectra of magnetized compact objects have three fathers. Gnedin and Sunyaev [24] predicted the lines theoretically. The third father, J. Trümper, and his colleagues discovered the lines in 1976 in the spectrum of Her X-1. Since then observations of the electron cyclotron lines have allowed the astronomers to measure the magnetic fields of X-ray pulsars.

The radiative transfer theory in a hot, fully ionized, and strongly magnetized atmosphere of a neutron star was completed [25] in 1983. More than that, high magnetic fields were shown [26] to affect the radiative transfer by polarizing the electron-positron vacuum. Strong anisotropy of the radiation and the vacuum polarization effects explain [25] the main features of the pulse shapes and their variations with photon energy in some X-ray pulsars.

It was a tricky job to construct the atmosphere models [27] of X-ray bursters: the atmosphere expands enormously during a burst with nearly Eddington luminosity. The job led to useful constraints on the parameters (masses, radii, distances, chemical compositions of the atmospheres) of some X-ray bursters [28].

One cannot build the atmosphere models without knowing the physics of atmospheric plasma. This plasma can be partially ionized and non-ideal; atoms and ions can be distorted by huge magnetic fields. The first realistic study [29] of ionization in the magnetized hydrogen atmospheres was done in 1974. A self-consistent model equation of state of non-magnetized hydrogen plasma constructed recently [30] takes account of the effects of pressure ionization and plasma non-ideality. The structure and radiative transitions of the hydrogen atoms moving in a strong magnetic field was a hard problem to solve (e.g., Ref. [31]): one should take into account strong electric fields induced in an atom-comoving reference frame. Similar but more complicated problem for the He^+ ion is being under study now [32].

Recent achievements are the realistic models [33] for the hydrogen, helium and iron atmospheres of the isolated neutron stars with low magnetic fields $B < 10^9$–10^{10} G. The radiation spectra from the H and/or He atmospheres are harder than the blackbody spectrum with the same effective temperature. Thus, the traditional blackbody interpretation of thermal radiation from the neutron stars may overestimate the effective temperature by a factor of 1.5–3 and lead to wrong conclusions on neutron star structure and evolution. The spectra from the iron atmospheres are closer to the blackbody but contain many spectral lines and photoionization jumps.

Many efforts were made to compose the first models [34, 35] of hot (the effective temperature $> 10^6$ K) hydrogen atmospheres of isolated neutron stars with strong magnetic fields $B \sim 10^{11} - 10^{13}$ G. The fields make the spectra softer than in the nonmagnetic stars but harder than the blackbody. The ion cyclotron absorption line can be generated in optics or UV. The radiation is highly polarized, peaked sharply along the magnetic field and has a fan-like beaming across the field. It is no problem now to calculate the radiative flux from a rotating neutron star with the nonuniform surface temperature and magnetic field distributions including the gravitational lensing near the star. All the atmosphere models are available in Internet (http://stella.ioffe.rssi.ru/Stars) and widely used by the astrophysical community.

Needless to say, the models were applied for interpretation of the spectra and light curves of the soft X-ray emission from several isolated neutron stars. The interpretation [36] of observations of the Geminga pulsar shows that the Geminga's surface can be very nonuniform. The fits of the X-ray spectrum of the Vela pulsar (detected with the ROSAT orbital observatory) with the hydrogen atmosphere models [37] give the distance to Vela consistent with other independent observations, contrary to the blackbody fits. The same is true for a few other neutron stars. The new generation of sensitive detectors and advanced atmosphere models will open a new era for the studies of mysterious surfaces and interiors of neutron stars.

2.2 Neutron star magnetospheres

The magnetosphere lies above the atmosphere. It is a place of violent processes: energetic particles are accelerated, radio and gamma-ray emission is formed, etc. In 1974 Tsygan proposed a model of generation of cosmic gamma-bursts [38] in the magnetospheres of vibrating neutron stars. The vibration energy was taken from the elastic stress-energy ($\sim 10^{47}$ erg) of the solid neutron-star core (such cores were popular in 1970s). Detailed theory of the electric fields around vibrating stars was developed later [39]. Now the vibrational model is being discussed in the literature as the model of the soft gamma repeaters.

X-ray emission from a hot spot on the surface of an X-ray pulsar is a good accelerator of electrons in the pulsar's magnetosphere [40]. Interaction of electrons with radiation near the magnetized neutron-star surface is affected by the electron cyclotron resonance. The resonance can strongly reduce the critical luminosity of the neutron stars [41] and modify the magnetospheric particle acceleration [42].

One needs the quantum relativistic theory to describe the cyclotron radiation (with possible maser effects) in a strongly magnetized plasma around the neutrons stars [43]. The plasma emits also the electron-positron annihilation radiation (see [44] and references therein) that depends on distribution functions of electrons and positrons.

Who could have imagined that the electric fields near a rotating neutron star are controlled by the general relativistic effect of drag of reference frame? But the effect is crucial [45] for the existence of radiopulsars with the spin periods about 1 s and the magnetic fields $\sim 10^{12}$ G. The electric fields are sufficient to accelerate the electrons, emitted from hot polar caps of radio pulsars, up to Lorentz factors $\sim 10^6$–10^7. The electrons generate gamma-quanta and the electron-positron pairs. The spectrum and beaming of such gamma-rays, the inverse current of positrons, the temperature of the hot polar caps and the efficiency of the electron-positron avalanche were modelled numerically [46].

The emission of particles and gamma-quanta by the radiopulsars, and (possibly) radioemission can be governed by an external magnetic field [47]. For a pulsar with the spin period of 1 s and the polar magnetic field $\sim 10^{12}$ G, the effect becomes important if the external field is about 0.5 – 3 G. For instance, such a field can be provided in a binary with a degenerate dwarf possessing an intrinsic field $\sim 10^8$ G.

A neutron star which has a non-dipolar magnetic field and enters an X-ray binary emits asymmetric X-ray radiation and produces an accelerating force [48]. After averaging over the neutron star spin, the force component along the spin axis survives. It may exceed gravitational attraction of the binary to the Galaxy. The effect is mostly pronounced in the low-mass X-ray binaries during the intense accretion onto the neutron stars. These systems may form the Galactic halo and escape partly into intergalactic space.

2.3 Internal structure and evolution

The internal structure is still a mystery. What is the composition of superdense neutron star cores? Nucleons and hyperons? Or maybe kaon condensates or strange quark matter? What is the equation of state: soft or stiff?

We started with the correct basic formalism for the electron thermal and electric conduction in degenerate surface layers of neutron stars without [49] and with [50] strong magnetic fields. These results were updated recently [51, 52, 53]. Thermodynamic properties of the surface layers, and the plasma screening of nuclear reactions in these layers were also studied [54, 55].

Transport properties in the neutron star cores have been analyzed too, particularly, the electron and muon thermal conductivities [56]. It was a surprise to find out (e.g., Refs. [57, 58]) that the electrical resistance in the nonsuperfluid cores across strong magnetic fields can be greatly enhanced, accelerating ohmic decay of the internal magnetic fields.

The quantized Feynman–Onsager vortices of neutrons in the superfluid and magnetized cores of the pulsars interact with magnetic proton fluxoids. This is a fantastic picture. While the pulsar spins down, the vortices are expelled from the core into the crust dragging the fluxoids. This triggers the glitches, and possibly reduces the pulsar magnetic moment [59].

Now a few words about the neutrino generation. Neutrinos can easily escape even from the superstars and are important cooling agents. Various neutrino energy loss mechanisms in the neutron star crusts and cores without and with strong magnetic fields were examined (e.g., Ref. [55]). One of them is the neutrino generation due to the electron bremsstrahlung by atomic nuclei in the neutron star crusts [60].

It was a tedious job to study the suppression of various neutrino reactions and heat capacity by neutron and/or proton superfluid in the neutron star cores (e.g., [61] and references therein). The suppression by the strong superfluidity was shown to be several orders of magnitude weaker than thought before. The neutrino-pair emission due to the Cooper pairing of nucleons in the neutron-star cores and crusts has been analyzed [62].

Cooling of the neutron stars depends on their internal structure and is a good tool to study this structure. Our recent cooling calculations for the stars with superfluid cores [61, 62] include properly the simultaneous effects of the neutron and proton superfluids. As a result, we have obtained preliminary constraints on the superfluid critical temperatures of neutrons and protons in the cores of PSR 0656+14, Geminga and several other pulsars by comparing the theory with the observational data on X-ray thermal radiation of these stars.

2.4 Neutron star magnetic fields

The magnetic fields, especially the superstrong ones, are always of interest. What is their origin? How do they evolve?

We have already described the studies of fields in the neutron star cores. But the fields can be confined in the crust, being independent of the core fields. The crustal fields can be generated by thermomagnetic effects in young neutron stars [63]. Urpin and coauthors [64, 65, 66, 67] elaborated the theory of the ohmic decay of the crustal fields in the cooling isolated neutron stars assuming the fields are supported by the crustal electric currents. The electric conductivity in a young star increases with its cooling and slows the decay. In a colder star (age $t > 10^5$ yr), the conductivity becomes temperature independent (determined by the electron – impurity scattering) and the field decay becomes especially slow. The decay depends on the cooling scenario (standard or rapid cooling) and on the equation of state in the stellar core (the stiffer the equation of state, the larger the crust and slower ohmic dissipation). The Joule heat can be sufficient to control the temperature of an old star ($t > 10^7$ yr). The field decay affects spin-down of the pulsars and, hence, their spin-down age. Observations of pulsar magnetic fields are more consistent with the standard cooling of neutron stars composed of matter with stiff equation of state. The theory can explain larger magnetic fields of the young pulsars in supernova remnants.

Another problem is the ohmic decay of the magnetic fields in the crusts of accreting neutron stars (see [66] and references therein). The accreted matter, which sinks within the crust, reheats the star and carries the field inside. The evolution of the magnetic field and spin period is associated with the accretion regime. The theory [66] considers the magneto-rotational evolution of neutron stars in the binaries with low-mass and massive counterparts. In particular, it gives a natural explanation of the existence of the millisecond pulsars.

References

[1] E. Milne, *Proc. R. Soc.* **A 158**, 324 (1937).

[2] P. A. M. Dirac, *Nature* **139**, 323 (1937).

[3] E. Teller, *Phys. Rev.* **73**, 801 (1948).

[4] G. Gamow, *Phys. Rev. Lett.* **19**, 759 (1967).

[5] F. J. Dyson, in *Aspects of Quantum Theory,* edited by A. Salam and E. P. Wigner, , p. 213 (Cambridge Univ., Cambridge, 1972).

[6] T. Damour and A. M. Polyakov, *Nucl. Phys.* **B 423**, 532 (1994).

[7] D. A. Varshalovich and A. Y. Potekhin, *Space Sci. Rev.* **74**, 259 (1995).
[8] D. Varshalovich, A. Potekhin and A. Ivanchik, *J. Journals* **1**, 7 (1997).
[9] A. I. Shlyakhter, *Nature* **25**, 340 (1976).
[10] T. Damour and F. J. Dyson, *Nucl. Phys.* **B 480**, 37 (1996).
[11] M. P. Savedoff, *Nature* **264**, 340 (1956).
[12] A. M. Wolfe, R. L. Brown and M. S. Roberts, *Phys. Rev. Lett* **37**, 179 (1976).
[13] S. A. Levshakov, *Vistas Astron.* **37**, 535 (1993).
[14] A. Y. Potekhin and D. A. Varshalovich, *Astron. Astrophys. Suppl. Ser.* **104**, 89 (1994).
[15] D. A. Varshalovich, V. E. Panchuk and A. V. Ivanchik, *Pis'ma Astron. Zh. (Engl. transl.: Astron. Lett.)* **22**, 8 (1996).
[16] S. A. Levshakov and D. A Varshalovich, *Monthly Not. R. Astron. Soc.* **212**, 517 (1985).
[17] C. B. Foltz, F. H. Chaffee and J. H. Black, *Astrophys. J.* **324**, 267 (1988).
[18] D. A. Varshalovich and S. A. Levshakov, *JETP Lett.* **58**, 237 (1993).
[19] D. A. Varshalovich and A. Y. Potekhin, *Pis'ma Astron. Zh. (Engl. transl.: Astron. Lett.)* **22**, 3 (1996).
[20] A. Y. Potekhin, A. V. Ivanchik, D. A. Varshalovich, K. M. Lanzetta, J. A. Baldwin, G. M. Williger and R. F. Carswell, *Astrophys. J.* , in press (1998).
[21] Yu. N. Gnedin, A. Z. Dolginov and A. I. Tsygan, *Pis'ma Zh. Exper. Teor. Fiz.* **10**, 441 (1969).
[22] Yu. N. Gnedin and G. G. Pavlov, *Sov. Phys.–JETP* **38**, 903 (1973).
[23] A. Z. Dolginov, Yu. N. Gnedin and N. A. Silant'ev, *Propagation and Polarization of Radiation in Cosmic Media* , (Nauka, 1979; Gordon and Breach, 1995).
[24] Yu. N. Gnedin and R. A. Sunyaev, *Astron. Astrophys.* **36**, 379 (1974).
[25] A. D. Kaminker, G. G. Pavlov and Yu. A. Shibanov, *Astrophys. Space Sci.* **91**, 167 (1983).
[26] G. G. Pavlov and Yu. N. Gnedin, in *Sov. Sci. Rev.,* edited by R. A. Sunyaev*,* **3**, p. 197 (Harwood Acad. Publ., 1984).
[27] V. E. Zavlin and Yu. A. Shibanov, *Sov. Astron.* **135**, 499 (1991).
[28] A. D. Kaminker, G. G. Pavlov, Yu. A. Shibanov et al., *Astron. Astrophys.* **220**, 117 (1989).
[29] Yu. N. Gnedin, G. G. Pavlov and A. I. Tsygan, *Zh. Exper. Teor. Fiz.* **66**, 421 (1974).
[30] A. Y. Potekhin, *Phys. Plasmas* **3**, 4156 (1996).
[31] A. Y. Potekhin and G. G. Pavlov, *Astrophys. J.* **483**, 414 (1997).
[32] V. G. Bezchastnov, G. G. Pavlov and J. Ventura, *Phys. Rev. A* **58**, 180 (1998).
[33] V. E. Zavlin, G. G. Pavlov and Yu. A. Shibanov, *Astron. Astrophys.* **315**, 141 (1996).
[34] G. G. Pavlov, Yu. A. Shibanov, V. E. Zavlin and R. J. Meyer, in *The Lives of the Neutron Stars,* edited by A. Alpar et al., NATO *ASI Ser. C* **450**, p. 71 (Kluwer, Dordrecht, 1995).
[35] Yu. A. Shibanov and V. E. Zavlin, *Astron. Lett.* **21**, 38 (1995).
[36] D. Page, D., Yu. A. Shibanov and V. E. Zavlin, *Astrophys. J.* **301**, 247 (1995).
[37] D. Page, D., Yu. A. Shibanov and V. E. Zavlin, in *Röntgenstrahlung from the Universe,* edited by H. U. Zimmermann et al., *, MPE Report* **263,**, p. 173 (1996).
[38] A. I. Tsygan, *Astron. Astrophys.* **44**, 21 (1975).
[39] A. G. Muslimov and A. I. Tsygan, *Astrophys. Space Sci.* **120**, 27 (1986).
[40] A. I. Tsygan, *Astrophys. Space Sci.* **77**, 187 (1981).
[41] I. G. Mitrofanov and G. G. Pavlov, *Mon. Not. R. Astron. Soc.* **200**, 1033 (1982).
[42] I. G. Mitrofanov and A. I. Tsygan, *Astrophys. Space Sci.* **84**, 35 (1982).
[43] V. G. Bezchastnov and G. G. Pavlov, *Astrophys. Space Sci.* **178**, 1 (1991).
[44] A. D. Kaminker, P. G. Mamradze and G. G. Pavlov, *Astrophys. Space Sci.* **192**, 175 (1992).
[45] A. G. Muslimov and A. I. Tsygan, *Mon. Not. R. Astron. Soc.* **255**, 61 (1992).
[46] V. D. Pal'shin and A. I. Tsygan, *Astron. Rep.* **40**, 385 (1996).
[47] A. I. Tsygan, *Mon. Not. R. Astron. Soc.* **292**, 317 (1997).

[48] V. D. Pal'shin and A. I. Tsygan, *Astron. Lett.* **24**, 131 (1998).
[49] D. G. Yakovlev and V. A. Urpin, *Sov. Astron.* **24**, 303 (1980).
[50] D. G. Yakovlev, *Astrophys. Space Sci.* **98**, 37 (1984).
[51] D. A. Baiko and D. G. Yakovlev, *Astron. Lett.* **22**, 708 (1996).
[52] A. Y. Potekhin and D. G. Yakovlev, *Astron. Astrophys.* **314**, 341; **327** 442 (1996).
[53] A. Y. Potekhin, G. Chabrier and D. G. Yakovlev, *Astron. Astrophys.* **323**, 415 (1997).
[54] D. G. Yakovlev and D. A. Shalybkov, in *Sov. Sci. Rev.,* edited by R. A. Sunyaev, **7**, p. 311 (Harwood Acad. Publ., 1989).
[55] D. G. Yakovlev and A. D. Kaminker, in *Equation of State in Astrophysics,* edited by G. Chabrier and E. Schatzman, , p. 214 (Cambridge Univ. Press, Cambridge, 1994).
[56] O. Y. Gnedin and D. G. Yakovlev, *Nucl. Phys.* **A 582**, 697 (1995).
[57] D. G. Yakovlev, in *Strongly Coupled Plasma Physics,* edited by H. M. Van Horn and S. Ichimaru, , p. 157 (Univ. Rochester Press, Rochester, NY, 1993).
[58] V. A. Urpin and D. A. Shalybkov, *Astron. Astrophys.* **294**, 117 (1995).
[59] G. Srinivasan, D. Bhattacharya, A. G. Muslimov and A. I. Tsygan, *Current Sci.* **59**, 31 (1990).
[60] P. Haensel, A. D. Kaminker and D. G. Yakovlev, *Astron. Astrophys.* **314**, 328 (1996).
[61] K. P. Levenfish and D. G. Yakovlev, *Astron. Lett.* **22**, 56 (1996).
[62] D. G. Yakovlev, A. D. Kaminker and K. P. Levenfish, in *Neutron Stars and Pulsars,* edited by N. Shibazaki, N. Kawai, S. Shibata and T. Kifune , p. 195 (Universal Acad. Press, Tokyo, 1998).
[63] V. A. Urpin, S. A. Levshakov and D. G. Yakovlev, *Mon. Not. R. Astron. Soc.* **219**, 703 (1986).
[64] V. A. Urpin and A. G. Muslimov, *Mon. Not. R. Astron. Soc.* **256**, 261 (1992).
[65] V. A. Urpin and K. A. Van Riper, *Astrophys. J.* **411**, L87 (1993).
[66] V. A. Urpin and D. Y. Konenkov, in *Neutron Stars and Pulsars,* edited by N. Shibazaki, N. Kawai, S. Shibata and T. Kifune , p. 171 (Universal Acad. Press, Tokyo, 1998).
[67] J. Miralles, V. A. Urpin and D. Y. Konenkov, *Astrophys. J.* , accepted (1998).