Physics – Uspekhi **52** (11) 1159 – 1167 (2009)

P N LEBEDEV PHYSICAL INSTITUTE — 75 YEARS

PACS numbers: 01.30.Bb, **01.65.+g**, 07.57.–c, 95.55.Jz

The Pushchino Radio Astronomy Observatory of the P N Lebedev Physical Institute Astro Space Center: yesterday, today, and tomorrow

R D Dagkesamanskii

DOI: 10.3367/UFNe.0179.200911i.1225

Contents

Abstract. The development of Russian (formerly Soviet) radio astronomy is indissolubly linked with the P N Lebedev Physical Institute (LPI), Russian Academy of Sciences. From the late 1940s, the institute conducted most of its radio astronomy research in the Crimea, at stations or on field trips; in the late 1950s, the center of gravity of research moved to the southern Moscow region, where one of the largest radio astronomy observatories in the country and in the world was developed within less than twenty years. The observatory unique instrumentation system is briefly reviewed in a historical perspective. Key research areas and some major achievements are outlined, and the prospects of the observatory as (currently) part of the LPI Astro Space Center are examined.

1. LPI, the cradle of Russian radio astronomy

The small, relatively young city of Pushchino located on the Oka River, Moscow region, is known worldwide as a large biological center whose research institutes bring together highly reputed, experienced scientists. In addition, Pushchino is home to the Radio Astronomy Observatory of the Astro Space Center, Lebedev Physical Institute, Russian Academy of Sciences (LPI PRAO ASC), one of the country's largest astronomy institutions. The observatory was established in the newly founded city in the late 1950s, under the name Okskaya Research Expedition. It was subsequently redesignated the LPI Radio Astronomy Station and obtained its current name, LPI PRAO ASC, in 1996, the year of its 40th anniversary.

R D Dagkesamanskii Pushchino Radio Astronomy Observatory, Astro Space Center, P N Lebedev Physical Institute, Russian Academy of Sciences, 142290 Pushchino, Moscow region, Russian Federation
Tel. (7-496) 733 01 85. E-mail: rdd@prao.ru

Received 25 May 2009, revised 4 June 2009
Uspekhi Fizicheskikh Nauk **179** (11) 1225 – 1235 (2009)
DOI: 10.3367/UFNr.0179.200911i.1225
Translated by Yu V Morozov; edited by A M Semikhatov

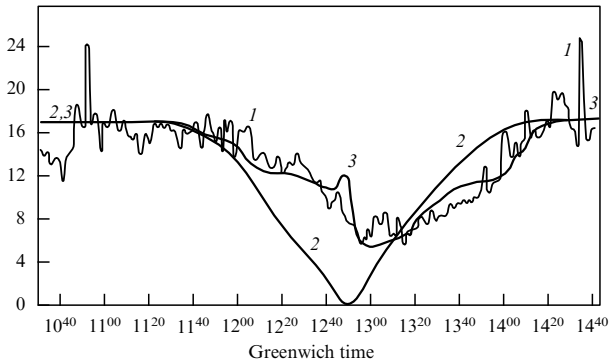

Figure 1. Observation of a total solar eclipse (20 May 1947) at the 1.5 m wave. Curve *1*, variations of the solar RF radiation flux density during the eclipse; *2*, variations of the visible solar disk area; *3*, eclipse of eruptive prominences and filaments. All curves are in arbitrary units.

Its birthday is assumed to be 11 April 1956, when the USSR Council of Ministers issued decree no. 2006-p that entrusted "the USSR Academy of Sciences with building premises for the LPI Radio Astronomy Station and establishing a radio telescope." The undoubtedly important decision was preceded by a decade of the rise and development of radio astronomy in this country, with LPI rightfully being considered its cradle.

In 1946, N D Papaleksi, head of a laboratory at LPI, discussing the possibility of radar location of the Sun, asked V L Ginzburg, then a young theorist, to calculate the level from which meter-range waves may be reflected. Ginzburg showed that this level lies in the upper solar corona. It was concluded that the solar diameter in the meter range should be noticeably greater than in the optical range. This inference was reliably confirmed by radio observation of the total solar eclipse in 1947 near the Brazilian coast by a group of LPI physicists headed by S E Khaikin [1] (Fig. 1). Encouraged by the first success, LPI scientists organized a few permanent observation stations in the Crimea and the Moscow region. The Crimean research station at Katsiveli became the largest of them. In 1953, the station did not have a single instrument

fit to conduct observations. However, several remarkable instruments were constructed within the next 3–4 years under the guidance of the gifted designer P D Kalachev. Worthy of special mention is the centimeter-wavelength telescope 32 m in diameter in the form of a stationary dish embedded in the earth, with the telescope beam operated within narrow limits by a feed moving in the focal plane. The first valuable results were obtained with these instruments. The most important of them are listed below:

• discovery of the solar supercorona (Vitkevich [2], 1953), which gave impetus to further exploration of the upper layers of the solar atmosphere and interplanetary plasma;

• discovery of polarization of the Crab Nebula radio emission (Kuz'min and Udal'tsov [3], 1957), which confirmed its synchrotron nature;

• the first observations of galactic nebulae in the 21 cm radio line performed in this country (Sorochenko [4], 1958).

In this early period of the development of radio astronomy in Russia, LPI physicists performed extensive applied studies that greatly contributed to the elaboration of the theory of radio communication and radio wave propagation. Taken together with basic research, this work promoted the development of the radiointerferometric method, whose advantages were so convincingly demonstrated by the first coordinate measurements in the lunar landing area of the Soviet Luna probes [5].

Observations made by the LPI team using antennas of the Crimean station were an important contribution to radio astronomy of that time. At the same time, they showed that local conditions seriously hampered further progress. First, it was impossible to establish a large high-resolution telescope in the relatively small area of the station, and second, the site had an intrinsically high interference level. Therefore, it was decided to create a large experimental radio astronomy base near Serpukhov on the right bank of the Oka River.

2. Building radio telescopes and the first research work in Pushchino

Soon after the aforementioned government decree, the Presidium of the USSR Academy of Sciences, the Moscow region and Serpukhov district Executive Committees of Working People's Deputies took decisions that enabled LPI radio astronomers to start working in the vicinity of the villages of Kharino and Pushchino on the right bank of the Oka River 15 km downstream from Serpukhov (late 1956).

Despite the lack of comfortable residences and reliable transport links, even with nearby Serpukhov, the work began at the end of 1956 with the laying of the foundation and installation of the first large radio telescope, presently widely known as the LPI RT-22 fully steerable 22-meter parabolic radio telescope. In the next year (1957), the building of another instrument was initiated. It was a giant cross-type meter-wave radio telescope consisting of two 1000×40 m parabolic cylinders.

The Pushchino radio astronomy team formed in parallel with the building of the world largest radio telescopes and their receiving facilities. Many researchers who are presently well known (Yu P Ilyasov, V I Slysh, A A Korchak, M V Konyukov, R I Noskova) moved to Pushchino by the late 1950s. However, all credit for the favorable atmosphere and fast-paced progress of the work during that early period should be given to the leading researchers of the Radio Astronomy Sector attached to the LPI Vibration Laboratory, including V V Vitkevich, P D Kalachev, A D Kuz'min, and A E Salomonovich, pioneering radio astronomers in this country who passed their experience and enthusiasm on to younger researchers. The work on the creation of unique radio telescopes supported by the energy and optimism of these people went on very successfully. Suffice it to say that the new RT-22 telescope, ready to operate, already stood erect on the formerly empty farmer field occupying a high Pushchino hill in May 1959, i.e., only 2.5 years after the foundation began to be laid. Five and a half years later, research projects could be initiated using the east–west arm of the wide-band cross-type radio telescope (DKR-1000).

Figure 2. Fully steerable centimeter and millimeter-wavelength RT-22 LPI radio telescope.

The LPI RT-22 radio telescope of the late 1950s for many years remained a unique instrument among the world's single dishes by virtue of its record-breaking high angular resolution. Kalachev, its design manager, proposed and realized new principles of suspension assembly and load distribution in the main mirror, which allowed both thermal deformations and those due to changes in spatial orientation to be reduced to a minimum. The resulting deviation of the mirror surface from the paraboloid of revolution was close to 0.3 mm, i.e., enough for efficient operation at the 8 mm wavelength with the angular resolution that is better than 2 minutes of arc [6] (Fig. 2). No other radio telescope had so high a resolving power at that time. Another 22-meter radio telescope with somewhat improved characteristics (RT-22) was constructed for the Crimean astrophysical observatory based on Kalachev's design only in 1966.

The wide-band cross-type radio telescope (DKR-1000) is another large radio telescope of the Pushchino observatory. It consists of two parabolic cylinders 1 km long with the width 40 m, respectively extended from east to west and from north to south. The first observations of radio sources using the east–west arm were made in late 1964. The north–south extension arm went into operation a few years later. The DKR-1000 differs from the best foreign analogs operative in a fixed and relatively narrow frequency range in that it allows simultaneous observations at any wavelengths in the range from 2.5 to 10 m (Fig. 3). Due to this property and the high sensitivity, the instrument even now provides a unique opportunity for a variety of research.

The angular resolution of RT-22, which was record high for individual radio telescopes available in the 1960s, in

Figure 3. East–west arm of the DKR-1000 LPI wide-band cross-type radio telescope.

combination with high sensitivity allowed many pioneering studies, such as imaging the Sun at radio wavelengths and identifying radio spots with active regions on its surface [7]. Equally fruitful RT-22-based research concerned the physical characteristics of lunar surface layers and the conditions in the atmosphere and on the surface of the planets. In 1962, Kuz'min summarized the data obtained with RT-22 in one of the first catalogs of centimeter radio sources. The high-frequency break in the spectrum of radio galaxy Cygnus-A found in the same observational series enabled the first experimental estimates of the age of this class of objects [9].

Finally, it was with the LPI RT-22 that Sorochenko and co-workers first observed a hydrogen radio recombination line in 1964. This line, resulting from electron transitions between levels 91 and 90 in the hydrogen atom, was detected in the spectrum of the Omega Nebula at the wavelength 3 cm [10] (Fig. 4). A similar observation was independently reported by A F Dravskikh and Z V Dravskikh, who worked on the large Pulkovo radio telescope and observed a line corresponding to electron transition from level 101 to level 100 of the hydrogen atom. Investigations of gaseous nebulae at the hydrogen, carbon, and helium radio recombination lines were the main research priorities of the RT-22 team for many years. The observation of these lines greatly contributed to solving problems such as the Stark broadening of spectral lines, the estimation of relative abundance of helium, and the analysis of the physical conditions in gaseous nebulae and star formation regions.

The first studies carried out with the DKR-1000 in the mid-1960s worthy of mention include observation of a large sample of radio sources at frequencies 38, 60, and 86 MHz [11–13] that helped find the dependence of the spectral index on the flux density for extragalactic radio sources [14, 15] (Fig. 5) and investigate the circumsolar and interplanetary plasma based on scintillations of compact radio sources [16]. In the late 1960s, simultaneous observations were made on the DKR-1000 east–west arm and smaller radio telescopes specially installed for the purpose near the cities of Pereslavl'-Zalessky (Yaroslavl' region) and Staritsa (Kalinin region). The observations for the first time permitted measuring the solar wind velocity relatively close to the Sun and at high helio-latitudes [17]. Also, the characteristic size of the inhomogeneities responsible for scintillations of radio sources was measured.

In the 1970s–1080s, the variable-baseline radio interferometer with the east–west arm of DKR-1000 as the main

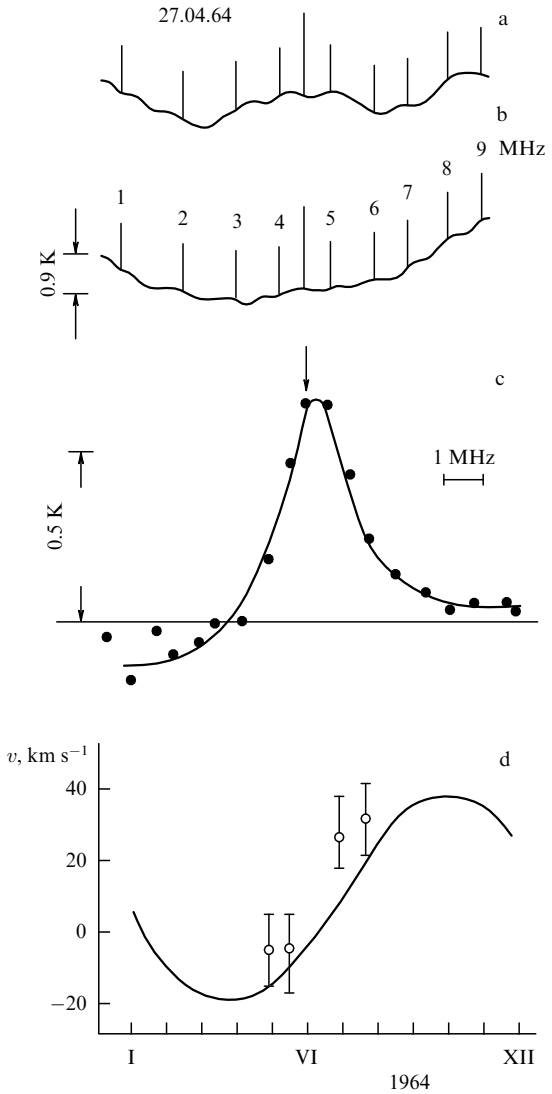

Figure 4. First spectrograms of the excited hydrogen $H_{91\alpha}$ line with a good signal/noise ratio obtained with the RT-22 LPI radio telescope. (a) Spectrogram in the direction of the Omega Nebula. (b) Reference spectrogram obtained with the antenna pointed away from the source. (c) Averaged difference between spectrograms (a) and (b) (April 1964); the arrow shows the line frequency calculated taking account of the Doppler effect. (d) Change in the observer radial velocity relative to the source during 1964; the curve illustrates the theoretical variation of radial velocity due to Earth's orbital motion.

element was used to measure the structural parameters of some 150 radio sources at the frequency 86 MHz with an angular resolution around 20″ [18]. Some information about the angular structure of several radio sources with higher resolution (up to 0.1″) was obtained from observations of their interplanetary scintillations with DKR-1000 [19].

After the discovery of a new class of radio sources (pulsars) had been reported in early 1968, it became clear that DKR-1000 best fulfills the objective of studying their radio emission. The first Pushchino pulsar, PP 0943, was discovered in the same year [20]. Many important data on the spectral characteristics of individual and averaged pulses of pulsars (Fig. 6), the frequency dependence of polarization of their radio emission, and the changes of pulse profiles with frequency were obtained within the following few years. A superdispersive pulse delay at low frequencies attributable to

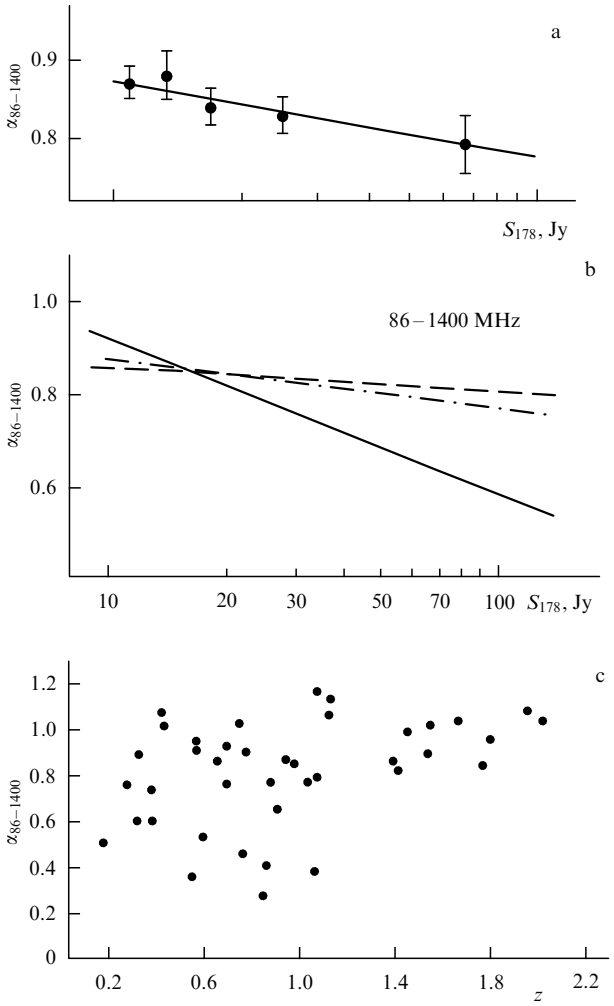

Figure 5. Regression dependence of the double-frequency spectral index $\alpha_{86-1400}$ on the current density S_{178} for all extragalactic sources, borrowed from the Third Cambridge Catalog (a); the same regression dependences presented separately for quasars (solid line), radio galaxies (dashed line), and unidentified radio sources (dashed-dotted line) from TCC (b); diagram (spectral index $\alpha_{86-1400}$–redshift z) for the same quasar sample (c).

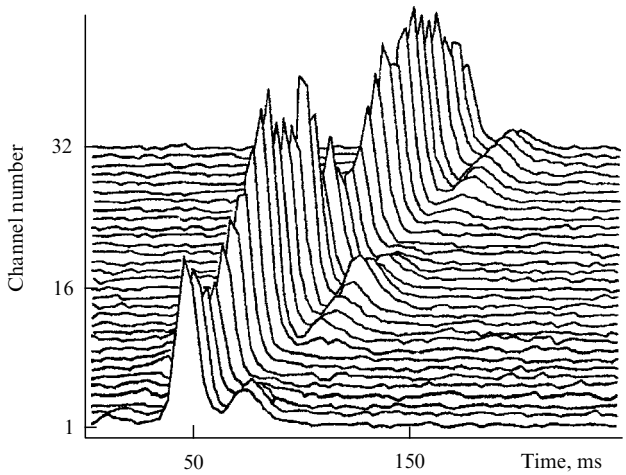

Figure 6. Averaged pulse of pulsar B0329+54 derived from observations with a 32-channel spectrum analyzer at 102.5 MHz. There is a well-apparent signal frequency amplitude modulation due to the Faraday effect in the interstellar medium.

Figure 7. The LPI Large Phased Array (BSA FIAN).

the deformation of magnetic dipole field lines in the light cylinder region was detected [21].

The use of the DKR-1000 north–south arm was much more restricted because operation of such a sophisticated phased array in a wide frequency range encounters difficulty. However, for the solution to problems requiring large signal integration time, the use of the antenna with a wide beam proved justified. Specifically, low-frequency carbon radio recombination lines in the spectrum of the Cassiopeia A supernova remnant were detected with the north–south arm of the radio telescope. The observation of radio lines resulting not only from electron transitions between adjacent energy levels (so-called α-transitions) but also from β- and γ-transitions revealed the presence of carbon atoms in energy states with principal quantum numbers $n \approx 750$ (!) [22]. These highly excited states are probably very close to marginally possible steady states determined by interactions between carbon atoms and background radio emission of the Galaxy. Such atoms are so large that during their lifetime in the excited state, they are multiply and continuously penetrated by neutral hydrogen atoms, which fail to perturb the corresponding energy levels.

The discovery of interplanetary scintillations of compact radio sources and thereafter the discovery of pulsars demonstrated that the 'confusion' effect due to the finiteness of the telescope resolving power (manifest as specific fluctuations in source records) is unessential for some important observational tasks. In such cases, it is possible to use large filled-aperture radio telescopes and there is no need for cross-type antennas or other complex telescopes. For this reason, Vitkevich decided in the late 1960s to build one more radio telescope in Pushchino, presently known as the Large Phased Array (BSA FIAN). It took relatively little time and money to install the BSA, comprising over 16,000 dipoles and covering an area of 7.2 hectares. The BSA has a record sensitivity in the meter wavelength range up to now [23] (Fig. 7).

Observations with BSA FIAN at a wavelength around 3 m ($\nu = 102$ MHz) began in 1974. (Unfortunately, Vitkevich did not live that long; he died in February 1972 at the peak of his carrier before his 55th birthday.) The high sensitivity of BSA allowed daily observations of interplanetary scintillations of about 150 compact radio sources. Such monitoring of the interplanetary medium permits studying the dynamics

of perturbations propagating from the Sun toward the periphery of the Solar System and can be used for short-term predictions of different types of geomagnetic excitation [24]. Regular mapping of interplanetary plasma over several decades revealed the dependence of the principal solar wind parameters on the phases of the solar activity cycle.

Interplanetary scintillations of compact radio sources carry information not only about the state of the nonuniform medium through which emission from radio sources propagates but also about the structure of these sources. For example, the power spectrum of scintillation-induced intensity variations of the incoming radiation from a 'point' source is totally determined by the inhomogeneity angular scale spectrum and the speed of diffraction pattern movement relative to the observer. For a source of the size comparable to or larger than the angular scale of inhomogeneities, such a spectrum is narrower and the variation amplitude is lower than for a smaller source with the same flux density. This permits judging on the compact details in radio sources and measuring the intensity and characteristic angular dimension of these details from the scintillation power spectra of the sources. Such observations made with the BSA FIAN for several hundred extragalactic radio sources of different classes revealed the degree of their compactness, physical conditions in the central regions of different types of galaxies, and distribution of compact radio sources in the Universe [19].

The data obtained with BSA FIAN were used to derive the radio luminosity function of clusters of galaxies and to determine the peculiarities of radio emission from those clusters rich in hot intergalactic gas [25]. Observation of the nearest Andromeda Nebula showed that this spiral galaxy has an extended radio halo responsible for most of its low-frequency radiation [26].

As expected, the most interesting results of BSA studies pertain to pulsars. The uniquely high sensitivity of this radio telescope permits observing the majority of pulsars in the northern sky. These observations and the data obtained with other radio telescopes were used to compile a catalog of averaged pulse profiles at different frequencies for more than 150 pulsars [27]. Some of them were shown to have several stable emission modes. For the most powerful pulsars, it is possible to register individual pulses of radiation and to study their microstructure with high temporal resolution.

An interesting line of research is the precision measurement of the pulse arrival time. Pulsars are known to be cosmic sources emitting radiation pulses at regular intervals. With this in mind, a group of LPI PRAO ASC scientists and specialists from the National Research Institute for Physico-technical and Radio Engineering Measurements (Gosstandart of the USSR) jointly proposed a new pulsar time scale [28]. It was approved by the appropriate commission of the International Astronomical Union (IAU) and accepted by several observatories around the world, including the LPI PRAO ASC. The accuracy of this scale was considerably improved after the discovery of so-called 'millisecond' pulsars, with the pulse period given by several milliseconds. Presently, the accuracy of the pulsar scale over roughly one-year intervals compares with and even surpasses that of the scale based on the best atomic standards. An important advantage of the pulsar time scale is that it is independent of concrete events at a given location and can be constructed using several widely spaced reference pulsars.

3. Current state of research tools at the Pushchino Radio Astronomy Observatory

Until 1990, the Pushchino Radio Astronomy Observatory (then the LPI Radio Astronomy Station) was the main section of the Department of Radio Astronomy of this institute. In 1990, the Astro Space Center (ASC) was organized as one of the LPI scientific divisions by merging the Department of Radio Astronomy and the Department of Astrophysics (headed by N S Kardashev) of the Space Research Institute, Russian Academy of Sciences. The merger has proved advantageous for both teams, e.g., in that it enabled the observatory to study compact radio sources using very large baseline radiointerferometry (VLBI), including ground–space interferometry. Presently, LPI RT-22 is equipped for operation in the VLBI network. Researchers from the LPI PRAO ASC participated in ground-based VLBI experiments and observations in the framework of the VLBI Space Observatory Programme/Highly Advanced Laboratory for Communication and Astronomy (VSOP/HALCA) project. The LPI PRAO ASC has a test-shop for testing space radio telescopes for future surveys. One of them, the 10-meter radio telescope to be installed aboard the Spektr-Radioastron space probe, was tested during September 2003–February 2004.

Despite a long history of the LPI PRAO ASC instruments (RT-22, DKR-1000, and BSA), their potential is far from exhausted and the possibilities for observational studies are continuously extended through joint efforts of the PRAO staff to maintain and further develop the unique experimental facilities of the observatory. This work includes modification of the illumination systems and beam-forming systems of the radio telescopes, and the development and manufacture of new amplifiers, radiometers, and spectrum analyzers. Taken together, the use of modern digital methods for signal registration, automation of observations, and creation of a local computer network enhance the efficiency of research and the quality of results. In the mid-1990s, when many broadcast stations occupied the operating range of BSA FIAN (101–104 MHz), specialists at the observatory undertook the enormous effort of tuning the antenna complex to allow it to operate in the frequency range 109–113 MHz. In this way, the life of the world's most sensitive meter-wave radio telescope was prolonged for further research work. But modification of BSA FIAN was not limited to tuning the antenna for operation in the new frequency range. At approximately the same time, the second beam-forming system of this antenna was proposed and created [29]. This enabled the scientists to simultaneously realize two research programs using the first multi-beam pattern to observe one object of interest and the second pattern to explore a different sky area.

One of the main objects of the ongoing PRAO research is the inhomogeneities of interplanetary and interstellar plasma examined by radio sounding that was extensively used by Vitkevich in his studies of the solar wind and supercorona. Today, it is applied with equal success to the analysis of data on inhomogeneous interstellar plasma obtained from its radio sounding by the radio emission of pulsars and compact extragalactic radio sources. Analysis of the effects produced by radio emission of pulsars and active galactic nuclei after its propagation through a medium between the source and the observer allows determining the principal parameters of the medium and even locating the layer most actively affecting the passing radiation in the line of sight [30]. Registration of

the so-called giant pulses of pulsars provides a unique opportunity for such studies. Suffice it to say that the enormous radiation power of certain pulses from the pulsar in the Crab Nebula coupled to the high sensitivity of the BSA and DKR-1000 radio telescopes allowed not only obtaining the average parameters of the scattering medium but also observing their variations over time intervals of several weeks, indicative of dynamic processes in this supernova remnant [31].

Worthy of special emphasis is the upper limit of energy density of gravitational waves in the Universe deduced from constraints on variations of pulse arrival time expected from pulsar interactions with these waves [32]. Relevant observations are carried out by PRAO researchers on the 64 m decimeter-wavelength radio telescope of the Special Design Department, Moscow Power Engineering Institute (SDD, MPEI), near the city of Kalyazin.

Another result stemming from the high sensitivity of the Pushchino meter-wavelength radio telescopes is the observation of radio emission from the X-ray source Geminga [33–35] and some other anomalous X-ray pulsars. Sometimes, a new radio source is identified from registration of a single unusually powerful pulse rather than due to the long-term accumulation of a signal with a known period, as is the case in the discovery of emission from X-ray pulsars. The main criterion for the cosmic origin of a registered signal is a dispersive delay of radio pulses observed at low frequencies relative to the pulses registered at higher frequencies [36].

As is known, a remarkable property of pulsars is the very high stability of their pulse periodicity. Therefore, registration of even a very small residual deviation of the pulse arrival time from the predicted value may give important information on both aforementioned effects of radiation propagation in the interstellar medium, the pulsar radio emission mechanisms, and the physical processes in its magnetosphere. Above all, it may suggest the existence of other bodies with large masses in the close vicinity of the pulsar. Moreover, such observations provide the sole possibility to validate the available models of the internal structure of neutron stars. The fact is that certain pulsars give evidence of 'glitches' in their pulse period. Such events might have occurred during the restructuring of the stellar crust (the so-called starquake) or even deeper layers of neutron stars. Investigations with the LPI PRAO ASC radio telescopes showed that pulse periods may demonstrate not only typical sharp variations but also more gradual changes; one of the pulsars from time to time shows alterations of the periods of both types [37]. Of crucial importance is the interdependence of the period variation amplitudes and the intervals between consecutive variations [38]. This finding permits empirically predicting the next appreciable change of the period and is therefore essential for understanding the phenomenon at large.

As mentioned above, the examination of interstellar atomic and molecular spectra is the main area of research using the RT-22 radio telescope. Much attention is given to the analysis of maser radio lines of interstellar molecules (first and foremost, water vapor molecules), besides the spectral lines of highly excited atoms of hydrogen, helium, and other elements described at greater length in [39]. Long-term regular observations of H_2O radio lines ($\lambda = 1.35$ cm) have been made in the spectra of almost 150 star formation regions and stars of late spectral classes. Some of these objects have been observed every month for approximately 30 years. This unique collection of data evidences dynamic processes in the vicinity of red giants and protostars. In certain cases, a thorough analysis of spectral changes in these objects suggests the existence of protoplanetary disks in star formation regions and permits elucidating the mechanisms of pumping the upper levels of water vapor molecules, as well as other physical conditions in maser line formation regions (see [40, 41]).

In the late 1980s, joint efforts of researchers affiliated with the LPI PRAO ASC and the Institute of Nuclear Research, Russian Academy of Sciences, resulted in the development of a radio astronomical method for detecting superhigh-energy cosmic neutrinos. The method is based on the idea proposed in the early 1960s by Askar'yan [42], who suggested identifying high-energy particles from bursts of Cherenkov radiation generated during the interactions of such particles and a dense dielectric medium. The radio astronomical method used the lunar surface layer as a giant target and large ground-based radio telescopes as highly sensitive detectors [43]. Today, this method, used not only in Russia but also in Australia, the USA, the Netherlands, and India, is considered the most promising tool for registration of neutrinos with energies over 10^{20} eV. The upper limits for high-energy neutrino fluxes achieved by the joint team with the Kalyazin 64 m radio telescope and by American researchers with the Goldstone 70 m telescope are already envisaged in some of the most exotic models of the Universe [44].

Previous scientific experience shows that research seemingly detached from real life yields results eventually finding practical application. It was mentioned in the preceding paragraphs that radioastronomical methods developed by LPI scientists in the past, along with the knowledge acquired during coordinate measurements in the lunar landing area of the Soviet Luna spacecraft and experiments on automatic Venus entry probes, proved to have many practical implications. It was also proposed to use pulsars as time keepers. Much interest has recently been shown in proposals formulated by scientists from the LPI PRAO ASC as early as the 1980s to develop a radioastronomical method for predicting geomagnetic and other perturbations in the circumterrestrial space caused by fluxes of high-energy particles ejected from the Sun.

The strong influence of such solar activity on the processes in Earth's atmosphere and magnetosphere, as well as its effect on human health, is widely known. With the further development of space research and increasingly extended manned space flight missions, the problem of 'cosmic weather' forecasting comes to the fore. As shown by LPI PRAO ASC researchers, regular observation of interplanetary scintillations of hundreds of radio sources provides a basis for the short-term forecast of the situation in interplanetary space. Yet another upgrade of the BSA FIAN telescope is currently underway, supported by the Institute of Applied Geophysics, State Hydrometeorology Committee, to ensure regular monitoring of the condition of the interplanetary plasma and the propagation of its perturbations threatening health of astronauts. Within the next two years, the LPI PRAO ASC is expected to constitute a most important element in the system of space weather forecasting.

The history of the scientific results obtained by LPI PRAO ASC researchers would be incomplete without reference to their theoretical works, the most prominent ones at least. The radio sounding technique proposed by Vitkevich in the early 1950s found wide application and is

extensively used in ongoing research designed to explore near-Sun and interplanetary plasma and to study physical conditions in the interstellar medium. These studies were greatly promoted by the works of Shishov [45, 46], who developed an analytic theory of strong scintillations, derived an equation for the fourth-order coherence function of the wave field, and obtained its solutions describing the development of strong fluctuations of coherent and partly coherent radiation intensity. Analysis of experimental findings brought theorists to the conclusion that low-frequency Alfvén waves generated in the upper solar chromosphere constitute the main source of heating of the solar corona and acceleration of the solar wind, while the structure of the corona, supercorona, and interplanetary plasma is primarily determined by the strength of the magnetic field at the coronal base [47, 48]. The evolution of rich galactic clusters, the phenomenon of galactic wind, and gas outflow from galactic clusters are considered in Konyukov's work [49, 50]. Finally, it is worth mentioning the theoretical interpretation of the wealth of observational pulsar data obtained by the LPI PRAO ASC in monograph [51].

The organization of the LPI Astro Space Center in 1990 provided an ample opportunity for extending the scientific contacts of the Pushchino Radio Astronomy Observatory with other astronomical institutions in Russia and abroad. In recent years, especially close collaboration has been developing between the PRAO and the Research Radiophysical Institute (Nizhny Novgorod); the Shternberg State Astronomical Institute; the Physical Faculty of Moscow State University; the Radioastronomic Institute of the Ukrainian Academy of Sciences (Khar'kov and Odessa); the Abastuman Astrophysical Observatory, Georgian Academy of Sciences; the Max Planck Institute of Radio Astronomy (Bonn, Germany); the National Radioastronomical Observatory and NASA (USA); and Australian, Dutch, and Japanese scientists. Every year, the LPI PRAO ASC organizes several astronomical schools, workshops, and conferences. The number of participants in annual conferences on topical problems of extragalactic astronomy held jointly with Saint Petersburg State University since the early 1980s has substantially increased recently. The 5th Annual School of Modern Astrophysics was held in July 2009. Annual scientific sessions of the LPI ASC based at the Pushchino observatory are widely reputed for the high level of panel discussions.

4. Further prospects

Speaking of further prospects for the PRAO and its experimental base, we must bear in mind newly emerging tendencies in the development of radioastronomical research throughout the world and the possibilities for the improvement of instruments, methods, and analysis of observational data. An increasing number of new radio telescopes designed and built all over the world in recent years and even decades are becoming centers of international research collaboration. The reasons behind such 'globalization' are obvious:

• very sensitive telescopes necessary to resolve increasingly complicated problems are highly sophisticated and expensive instruments;

• effective operation of huge radio telescope facilities is possible at only a few sites on the Earth having appropriate climatic conditions and low background noise levels;

• construction of a new radio telescope designed to surpass the existing instruments is a significant technological challenge implying integration of experience and the capabilities of advanced research institutions and industry.

We note a few projects targeted at the creation of radio telescopes of the 21st century, such as the Atacama Large Millimeter Array (ALMA), currently under construction in the Atacama Desert (5,000 m above sea level, Chili) and the Square Kilometer Array (SKA), a centimeter and millimeter-wave radio telescope with the effective area 1 km^2 to be built in a desert region of Western Australia or South Africa. The participation of our country in such projects is of primary importance not only for researchers but also for the radiotechnical industry. At present, the LPI PRAO ASC is a member of a European consortium pursuing the design and construction of the SKA, and the ASC representative has the status of observer on the International Coordination Committee. The SKA project will be implemented over the next decade and completed in 2021. It is highly important to maintain and strengthen the position of the Russian side in this project, which involves not only European countries but also the USA, Canada, Australia, South Africa, India, China, and New Zealand.

Listed below are the main issues to be explored using the ALMA, SKA, and LOFAR (a low-frequency array being built in the Netherlands jointly with Germany, France, and some other European states):

• the early stages of the evolution of the Universe, including the reionization epoch;

• the physical nature of dark matter and dark energy;

• star formation processes in our Galaxy and galaxies billions of light years away;

• physical processes in active galactic nuclei;

• the search for variable radio sources of different natures;

• the detection of superhigh-energy particles;

• the radio astronomy of the Sun and objects of the Solar System;

• the origin of life in the Universe and the search for signals from extraterrestrial intelligence, etc.

In short, there are a great variety of problems expected to be resolved with the help of these wonderful instruments. The universal applicability of such systems accounts for their high cost. For example, the estimated cost of SKA exceeds 1 billion US dollars. Therefore, almost all such projects imply joint efforts of several states and even the entire world community.

Also, these telescopes will be instrumental in dealing with problems that currently face radio astronomers and those likely to arise in the future. In other words, universal instruments are much less subject to obsolescence than devices designed to solve a concrete task. Active Russian involvement in such projects would guarantee our researchers access to the world's best radio telescopes, at least in the first half of the 21st century.

Although indispensable, participation in international research programs alone is insufficient for the further development of radio astronomy in this country. A new domestic radio telescope is needed that, even if not universal in the full sense of the word, would significantly surpass the existing instruments in terms of one or several parameters. It might be a low-cost alternative to international projects that would nevertheless provide new observational opportunities and allow astronomers to more efficiently resolve selected problems. Given the correct choice of such problems, their number may grow in proportion to the number of parameters

that make the new instrument superior to the available ones. This line of reasoning is fairly well illustrated by the example of the DKR-1000 LPI telescope. It was originally designed to elucidate the distribution of radio sources by flux densities in an attempt to answer the question (widely discussed in the late 1950s) of whether our Universe actually evolves. But the answer had been obtained before the east–west antenna was put into operation. Therefore, the instrument was used to observe interplanetary scintillations of radio sources, measure the solar wind velocity, and study the spectra and structure of extragalactic radio sources, radio lines of giant carbon atoms, and pulsars. The success of these studies with DKR-1000 was based on the high sensitivity and wide frequency range of the instrument, a combination that to date remains a unique characteristic of meter-wavelength radio telescopes.

Therefore, further research activities using the PRAO ASC LPI will not be confined to participation in the above international projects for the creation of large universal telescopes of the 21st century. Substantial modernization of the PRAO ASC experimental base is in order. A recent update of the RT-22 radio telescope was undertaken with a view to expanding its application not only to radioastronomical investigations proper but also as the antenna of a tracking station in the framework of the Radioastron project and possibly other space projects. Modification of the telescope receiving complex is underway to extend the possibilities of the tool in measuring both the continuous spectrum and spectral radio lines.

The current updating of the unique meter-wavelength complex of the observatory has the objective of improving the sensitivity and interference mitigation of the DKR-1000 east–west arm and BSA FIAN, as well as to broaden their fields of view. It is believed that the BSA should have at least three fully independent beam-forming systems. The one designed to monitor interplanetary plasma conditions will form 64 stationary beams densely spanning over declinations in the range from -8° to 55° in the plane of the local celestial meridian (the celestial meridian through the zenith at the observation point). The remaining multibeam patterns will have fewer beams (as they do today), but will be switchable in a broader declination range (from -20° to 90°).

Simultaneously, a digital system for data collection from the sections of the east–west antenna of the DKR-1000 is being developed; it will include a digital beam-forming system of this telescope. Signals from all sections will be amplified and converted into digital form without the loss of information over the entire working frequency band (30–120 MHz). All further steps of data collection and processing will be based on modern digital methods to enhance the reliability of telescope performance and the flexibility and interference mitigation of the entire system.

New problems have arisen and even new objects of study have emerged over the decades since the last of the three large radio telescopes of the LPI PRAO ASC was deployed. Today, astronomers frequently focus attention on phenomena developing on time scales from parts of a day down to fractions of a second. Some of them are certainly related to the effects of radiation distribution in interstellar and intergalactic media. Therefore, their investigation yields valuable information not only on the structure of radio sources but also on the characteristics of inhomogeneities in the medium separating the source and the observer, such as a nonuniform electron concentration or a gravitational field. These phenomena also include gravitational lensing, abnormally strong scattering, or focusing radio emission from compact radio sources.

It was shown that fast variability often reflects real episodes of intense energy release on small time scales. A characteristic example of such events is given by gamma-bursts and so-called X-ray and gamma-transients. It is not surprising that these phenomena are most frequently observed in the gamma and X-ray ranges, bearing in mind that monitoring all kind of burst-like phenomena is especially well organized in these ranges using systems with extremely wide fields of view. Today, there are no similar systems operative in other frequency ranges. Measurement of the radiation flux from an object producing gamma-ray bursts in alternative wavelength ranges is also important for the elucidation of the nature of these enigmatic phenomena.

In other words, monitoring transient sources and bursts of radiation in frequency ranges other than the gamma and X-ray ranges is considered a most challenging astrophysical problem. Such monitoring in the radio band, for example, in the meter-wavelength range, appears quite possible and can be organized within a rather short time and at a relatively low cost. Other objects and phenomena associated with intense sporadic bursts or marked variations of the radio emission intensity include:

- giant pulsar pulses with fluxes hundreds of times greater than the pulse-averaged flux (one of the most interesting astrophysical phenomena);
- magnetars and other anomalous X-ray pulsars;
- supernovae flares;
- rapid flux variability of extragalactic radio sources;
- active processes in the Sun and near-Sun plasma;
- very short bursts of radio emission accompanying extensive atmospheric showers or interactions of high-energy cosmic rays with moon regolith.

Such a large number of topical issues can be addressed only after radical modernization of the LPI PRAO ASC experimental tools. On the other hand, recent progress in radiophysics and antenna and computer technologies greatly promotes the solution to many technological problems that were considered insurmountable some 10–20 years ago. Sometimes, creation of a new system using modern technologies to solve a specific problem may be a more cost-competitive option than modification of the existing instrument. Taking this fact into consideration, PRAO scientists and engineers proposed the concept of a new-generation meter-wavelength radio telescope. The instrument will comprise a core component and several outer stations with the central effective area at least 60% of the total one. Both the core and the peripheral antennas will consist of a set of identical modules, each containing, for example, 16 orthogonal wide-band dipoles effectively receiving signals in the range from 35 to 75 MHz. Signals picked up by individual modules will be combined after digitization. Such a beam-forming system is expected to ensure simultaneous registration of cosmic radio emission from more than 1000 directions, spanning the entire field of view of the instrument (about 2 sr).

Presently, simulation of individual modules (Fig. 8) and the development of a system for signal digitization and summation are underway at the observatory. The estimated cost of such system is 120 mln rubles. Implementation of this project would both substantially promote a solution to the aforementioned basic problems and enhance the reliability of cosmic weather forecasts. Before that, the forecasting will be done using observations with the BSA radio telescope.

Figure 8. A scale model of the meter-wave radio telescope module of the new generation being developed at the LPI PRAO ASC.

References

1. Khaikin S E, Chikhachev B M *Dokl. Akad. Nauk SSSR* **58** 1923 (1947)
2. Vitkevich V V *Astron. Zh.* **32** 106 1955
3. Kuz'min A D, Udal'tsov V A *Astron. Tsirk.* **187** 14 1957
4. Sorochenko R L *Astron. Zh.* **38** 478 (1961) [*Sov. Astron.* **5** 355 (1961)]
5. Vitkevich V V et al. *Dokl. Akad. Nauk SSSR* **132** 85 (1960) [*Sov. Phys. Dokl.* **5** 457 (1969)]
6. Kalachev P D, Salomonovich A E *Tr. Fiz. Inst. Akad. Nauk SSSR* **17** 13 (1962)
7. Salomonovich A E *Tr. Fiz. Inst. Akad. Nauk SSSR* **17** 42 (1962)
8. Kuz'min A D et al. *Astron. Zh.* **37** 975 (1960) [*Sov. Astron.* **4** 909 (1961)]
9. Kardashev N S, Kuz'min A D, Syrovatskii S I *Astron. Zh.* **39** 216 (1962) [*Sov. Astron.* **6** 167 (1962)]
10. Sorochenko R L, Borodzich É V *Dokl. Akad. Nauk SSSR* **163** 603 (1965) [*Sov. Phys. Dokl.* **10** 588 (1966)]
11. Artyukh V S, Vitkevich V V, Dagkesamanskii R D *Astron. Zh.* **44** 984 (1967) [*Sov. Astron.* **11** 792 (1968)]
12. Aslanyan A M et al. *Astrofiz.* **4** 129 (1968) [*Astrophys.* **4** 39 (1968)]
13. Artyukh V S, Dagkesamanskii R D, Vitkevich V V, Kozhukhov V N *Astron. Zh.* **45** 712 (1968) [*Sov. Astron.* **12** 567 (1969)]
14. Dagkesamanskii R D *Astrofiz.* **5** 297 (1969) [*Astrophys.* **5** 140 (1969)]
15. Dagkesamanskii R D *Nature* **226** 432 (1970)
16. Vitkevich V V, Antonova T D, Vlasov V I *Dokl. Akad. Nauk SSSR* **168** 55 (1966) [*Sov. Phys. Dokl.* **11** 369 (1966)]
17. Vitkevich V V, Vlasov V I *Astron. Tsirk.* **396** 1 (1966)
18. Volodin Yu V, Gubanov A G, Dagkesamanskii R D *Tr. Fiz. Inst. Akad. Nauk SSSR* **189** 173 (1988) [Translated into English: in *Clusters of Galaxies and Extragalactic Radio Sources* (Proc. of Lebedev Phys. Inst., Vol. 189, Ed. A D Kuz'min) (New York: Nova Sci. Publ., 1989) p. 229]
19. Artyukh V S *Tr. Fiz. Inst. Akad. Nauk SSSR* **189** 223 (1988)
20. Alekseev Yu I et al. *Dokl. Akad. Nauk SSSR* **187** 1019 (1969) [*Sov. Phys. Dokl.* **14** 781 (1970)]
21. Davies J G et al. *Mon. Not. R. Astron. Soc.* **211** 57 (1984)
22. Lekht E E, Smirnov G T, Sorochenko R L *Pis'ma Astron. Zh.* **15** 396 (1989) [*Sov. Astron. Lett.* **15** 171 (1989)]
23. Vitkevich V V, Ilyasov Yu P, Kutuzov S M *Izv. Vyssh. Uchebn. Zaved. Radiofiz.* **16** 1904 (1973) [*Radiophys. Quantum Electron.* **16** 1482 (1973)]
24. Vlasov V I *Geomagn. Aeronom.* **21** 441 (1981)
25. Gubanov A G, Dagkesamanskii R D *Tr. Fiz. Inst. Akad. Nauk SSSR* **189** 43 (1988) [Translated into English: in *Clusters of Galaxies and Extragalactic Radio Sources* (Proc. of Lebedev Phys. Inst., Vol. 189, Ed. A D Kuz'min) (New York: Nova Sci. Publ., 1989) p. 51]
26. Volodin Yu V, Dagkesamanskii R D *Astrofiz.* **13** 617 (1977) [*Astrophys.* **13** 367 (1977)]
27. Izvekova V A et al. *Austr. J. Phys.* **32** 25 (1979)
28. Il'in V G et al. *Dokl. Akad. Nauk SSSR* **275** 835 (1984) [*Sov. Phys. Dokl.* **29** 252 (1984)]
29. Kutuzov S M et al. *Tr. Fiz. Inst. Akad. Nauk* **229** 3 (2000)
30. Shishov V I et al. *Astron. Astrophys.* **404** 557 (2003)
31. Kuzmin A D, in *Proc. of the 363 WE-Heraeus Seminar on Neutron Stars and Pulsars* (MPE-Report, 291, Eds W Becker, H H Huang) (Garching bei Münich: Max Planck Inst. Für Extraterrestrische Physik, 2007) p. 72
32. Potapov V A, in *Problemy Sovremennoi Astrometrii: Trudy Pervoi Moskovskoi Astrometricheskoi Shkoly, Zvenigorod, 2007* (Problems of Modern Astrometry)
33. Kuz'min A D, Losovskii B Ya *Pis'ma Astron. Zh.* **23** 323 (1997) [*Astron. Lett.* **23** 283 (1997)]
34. Shitov Yu P, Pugachev V D *New Astron.* **3** 101 (1997)
35. Malofeev V M, Malov O I *Nature* **389** 697 (1997)
36. Shitov Yu P et al. *Astron. Zh.* **86** 607 (2009) [*Astron. Rep.* **53** 561 (2009)]
37. Shabanova T V *Astron. Zh.* **86** 505 (2009) [*Astron. Rep.* **53** 465 (2009)]
38. Shabanova T V *Astrophys. J.* **700** 1009 (2009)
39. Sorochenko R L, Gordon M A *Rekombinatsionnye Radiolinii: Fizika i Astronomiya* (Recombination Radio Lines: Physics and Astronomy) (Moscow: Fizmatlit, 2003) [Translated into English: *Radio Recombination Lines: Their Physics and Astronomical Applications* (New York: Springer, 2009)]
40. Lekht E E, Pashchenko M I, Tolmachev A M *Astron. Zh.* **84** 592 (2007) [*Astron. Rep.* **51** 531 (2007)]
41. Lekht E E, Munitsyn V A, Krasnov V V *Astron. Zh.* **84** 30 (2007) [*Astron. Rep.* **51** 27 (2007)]
42. Askar'yan G A *Zh. Eksp. Teor. Fiz.* **41** 616 (1961) [*Sov. Phys. JETP* **14** 441 (1962)]
43. Dagkesamanskii R D, Zheleznykh I M *Pis'ma Zh. Eksp. Teor. Fiz.* **50** 233 (1989) [*JETP Lett.* **50** 259 (1989)]
44. Beresnyak A R et al. *Astron. Zh.* **82** 149 (2005) [*Astron. Rep.* **49** 127 (2005)]
45. Shishov V I *Izv. Vyssh. Uchebn. Zaved. Radiofiz.* **11** 866 (1968) [*Radiophys. Quantum Electron.* **11** 500 (1968)]
46. Shishov V I *Zh. Eksp. Teor. Fiz.* **61** 1399 (1971) [*Sov. Phys. JETP* **34** 744 (1972)]
47. Chashei I V, Shishov V I *Geomagn. Aeronom.* **17** 984 (1977)
48. Chashei I V, Shishov V I *Astron. Zh.* **65** 157 (1988) [*Sov. Astron.* **32** 81 (1988)]
49. Konyukov M V *Tr. Fiz. Inst. Akad. Nauk SSSR* **189** 64 (1988) [Translated into English: in *Clusters of Galaxies and Extragalactic Radio Sources* (Proc. of Lebedev Phys. Inst., Vol. 189, Ed. A D Kuz'min) (New York: Nova Sci. Publ., 1989) p. 81]
50. Konyukov M V *Tr. Fiz. Inst. Akad. Nauk SSSR* **189** 113 (1988) [Translated into English: in *Clusters of Galaxies and Extragalactic Radio Sources* (Proc. of Lebedev Phys. Inst., Vol. 189, Ed. A D Kuz'min) (New York: Nova Sci. Publ., 1989) p. 147]
51. Malov I F *Radiopul'sary* (Radio Pulsars) (Moscow: Nauka, 2004)