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Joint scientific session of the Physical Sciences Division of the Russian Academy of Sciences and Research Council of the P N Lebedev Physical Institute of the Russian Academy of Sciences honoring the 90th birthday of Academician V L Ginzburg (4 October 2006)

A joint scientific session of the Physical Sciences Division of the Russian Academy of Sciences (RAS) and Research Council of the P N Lebedev Physical Institute, RAS honoring the 90th birthday of Academician V L Ginzburg was held in the Conference Hall of the P N Lebedev Physical Institute, RAS on 4 October 2006. The following reports were presented at the session:

(1) **Gurevich A V** (P N Lebedev Physical Institute, RAS, Moscow) "Nonlinear effects in the ionosphere";

(2) **Kardashev N S** (P N Lebedev Physical Institute, RAS, Moscow) "The radio Universe";

(3) **Ptuskin V S** (Institute of Terrestrial Magnetism, Ionosphere and Radiowave Propagation, RAS, Troitsk, Moscow region) "On the origin of galactic cosmic rays";

(4) **Maksimov E G** (P N Lebedev Physical Institute, RAS, Moscow) "What is known and what is unknown about HTSCs";

(5) **Belyavsky V I, Kopaev Yu V** (P N Lebedev Physical Institute, RAS, Moscow) "Ginzburg – Landau equations for high-temperature superconductors";

(6) **Tsytovich V N** (A M Prokhorov Institute of General Physics, RAS, Moscow) "Polarization effects in a medium: from Vavilov – Cherenkov radiation and transition radiation to dust-particle pairing, or the development of one of V L Ginzburg's ideas from 1940 to 2006".

Extended reports Nos 1 and 4 in the form of reviews will be published in subsequent issues of *Physics – Uspekhi*. An abridge version of the other four papers is given below.

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The radio Universe

N S Kardashev

1. Introduction

In the 20th century, the revolutionary development of physics and technology made it possible to carry out studies of the Universe in all ranges of the electromagnetic spectrum. The discovery of cosmic radio emission from the Galaxy (K Jansky, 1932), from the Sun (G Reber, J Hey, J Southworth (1942 – 1944), and from galactic and extragalactic radio sources [G Reber, J Hey, S Parsons, J Phillips, J Bolton, G Stanley, M Ryle, F Smith (1942 – 1948)]; progress in radio astrospectroscopy and radio interferometry, and the discovery of quasars, pulsars, and cosmic microwave background in combination with deep analysis and modeling of observed astronomical objects on the basis of rapidly developing theoretical physics (quantum mechanics and General Relativity most of all) allowed building up the modern picture of the structure and evolution of individual astronomical objects and the multicomponent model of the entire Universe. In this rapidly developing scientific research, radio astronomical methods have played an outstanding role and will play it in years to come. Most references to the early period of radio astronomical studies can be found in the reference book [1], and the history of the development of radio astronomy in the USSR is described in Refs [2 – 6].

The first radio astronomical research in the USSR was initiated by Academician N D Papaleksi, the famous radio physicist, who was the head of the Laboratory of Oscillations at the Lebedev Physical Institute in the 1940s. When thinking over the possibility of the radio location of planets and the Sun, at the beginning of 1946 Papaleksi asked V L Ginzburg to investigate the reflection conditions of radio waves [7, p. 127]. For the Sun this turned out to be a difficult problem;

V L Ginzburg (left) and I S Shklovsky discuss problems in the theory of radio emission from solar corona (Rio de Janeiro, 1947).

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Participants in the expedition to observe a solar eclipse in Brazil on May 20, 1947 on the deck of the motor ship *Griboedov*: S E Khaikin (far right, first row), Ginzburg and B M Chikhachev (fourth and ninth, respectively, second row), and I S Shklovsky (second from right, third row).

however, estimates and the analysis of peculiarities of the intrinsic emission of the Sun proved to be very interesting and initiated a series of pioneering papers on the physics of solar and galactic radio emission [7 – 20].

To observe the total eclipse of May 20, 1947, Papaleksi organized a big expedition to Brazil, in which Ginzburg and I S Shklovsky participated, in addition to experimentalists. A radio telescope (a re-equipped radar station with a receiver tuned to a wavelength of 1.5 m) was mounted on the deck of the motor ship *Griboedov*, and the ship itself turned following the Sun. The results of observations reliably showed for the first time that the meter-wavelength radio emission from the Sun is generated in the corona, in accordance with theoretical predictions. The discovery certificate was issued to Papaleksi, S E Khaikin, and B M Chikhachev. It was the first significant radio astronomical experiment in the USSR.

2. The most interesting results of recent years

The ultraprecise mapping of fluctuations of cosmic microwave background in the short-wavelength centimeter and millimeter ranges using the WMAP satellite (Wilkinson Microwave Anisotropy Probe) continues [21]. According to these data, the cosmological model is described by six dimensionless parameters:

$$\Omega_{\rm m} h^2 = 0.1277 + 0.0080/-0.0079\,,$$
$$\Omega_{\rm b} h^2 = 0.02229 \pm 0.00073\,,$$
$$h = 0.732 + 0.031/-0.032\,, \qquad n_{\rm s} = 0.958 \pm 0.016\,,$$
$$\tau = 0.089 \pm 0.030\,, \qquad \sigma_8 = 0.761 + 0.049/-0.048\,.$$

Here, $\Omega_{\rm m}$ is the present matter density related to the critical density value, $\Omega_{\rm b}$ is the same quantity for baryons, h is the modern value of the Hubble constant in the units of 100 km s^{-1} Mpc^{-1}, $n_{\rm s}$ is the power law index of the scalar density perturbations, τ is the optical depth, and σ_8 is the amplitude of density fluctuations on the scale of 8 Mpc. The combination of the WMAP data with observations from the Hubble Space Telescope suggests that the vacuum density in the Universe, $\Omega_\Lambda = 0.716 \pm 0.055$, puts constraints on the parameter of the dark energy equation of state, $w = -1.08 \pm 0.12$, and points to the very small deviation in the total matter density from the critical density: $\Omega_{\rm c} = -0.014 \pm 0.017$.

Even more precise data, including polarization measurements, are expected to be obtained by the Planck mission scheduled for launch in 2008 [22].

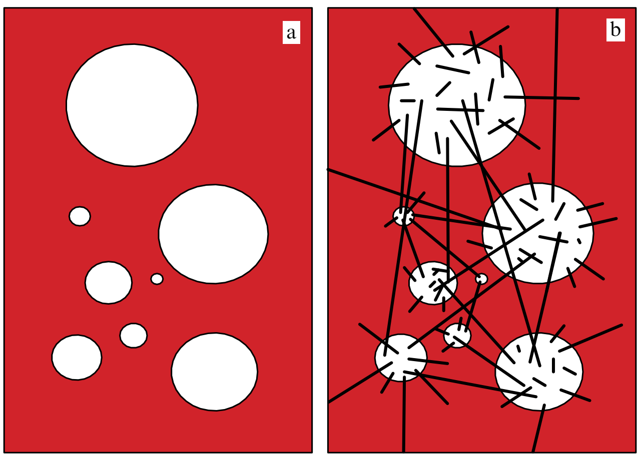


Figure 1. Models of the multielement Universe (Multiverse) without (a) and with (b) tunnels.

New prospects in cosmology are related to the model of the multicomponent Universe (the Multiverse), in which the inflationary stage occurs in different space regions at different instants of times (Fig. 1). Generally, the Multiverse can be infinite in space and time and infinitely diverse. Experimentally, such a model can be checked only if there are topological tunnels — wormholes [23, 24]. Paper [24] argues that wormholes can be supported by a strong magnetic field threading them (with a small portion of phantom energy), so observations of entrances to the tunnels can reveal some distinctive features like the monopole structure of a magnetic field, one-sided jets of relativistic particles, and the absence of an event horizon. However, for many indications such objects may have similarities with already observed galactic or extragalactic compact synchrotron sources.

Systematic studies of extragalactic sources [25] suggest that ultracompact objects which cannot be resolved with ground-based radio interferometers are observable in many galactic nuclei with supermassive black holes (or entrances to the tunnels) are located. The well-known radio galaxy M87 provides an example. Clearly, only with the use of space interferometers can the structure of such objects be studied and their nature understood.

A new (for radio astronomy) class of extragalactic sources emerging after gamma-ray bursts appears very intriguing. According to current models, these objects result from the explosion triggered in merging two stellar-mass black holes, or a black hole and a neutron star, or two neutron stars. Quite unexpectedly, the spectrum of these radio sources has been found to be inverted during the first days after the explosion [26, 27], i.e., it increases towards short wavelengths. This explains why the radiation flux from such sources barely changes with redshift and one can observe even the most distant explosions in the radio band [28]. Apparently, only with radio interferometers will we be able to study the structure of these objects and, in particular, to determine the directivity, dynamics and total energy of the explosion.

New discoveries in galactic radio astronomy are also very interesting. Observations of giant radio pulses from the Crab pulsar carried out at Pushchino and Kalyazin [29] (after special data processing to exclude pulse smearing due to the dispersion of radio waves propagating in the interstellar medium) revealed that some pulses have a giant amplitude with the flux exceeding that from the Sun and a brightness temperature of 10^{40} K. This means that the electromagnetic energy density in the pulse generation region exceeds that of the magnetic field of the neutron star itself, which is a big problem for the physical modeling of such regions.

In paper [30], the radio image of rapidly varying radio source Cygnus X-3 was obtained for the first time. This source represents a close binary system containing a black hole with a mass around five solar masses and a Wolf-Rayet star supplying matter to the accretion disk around the black hole. Studies of this system with high angular resolution will allow measurements of the structure and parameters of the plasma, relativistic particles, and magnetic field in the vicinity of black holes.

In 2006, a new class of pulsars was reported [31]: radio pulses with a period of 5.54 s were discovered from variable X-ray source XTE J1810-197. However, the radio emission spectrum turned out to be flat (in ordinary pulsars, the spectrum sharply decreases with frequency). This calls for a new model for coherent emission from these objects and allows studying them with record angular resolution at short wavelengths.

Of great interest are ongoing studies of ultracompact maser sources located in the Sstars and planetary systems formation regions. Observations of one of the most powerful maser sources in our Galaxy W3 (OH) at the wavelength of water vapor 1.35 cm [32] revealed the presence of a strong radio source which cannot be resolved by ground-based interferometers. Studies of star-forming galaxies show the presence of many narrow superpower lines (megamasers) at wavelengths of 1.35 cm (H_2O) and 18 cm (OH) generated in ultracompact regions (the upper limit to their size is inferred only from flux scintillations on inhomogeneities of the interstellar plasma) [33, 34].

3. Prospects of research

The prospects of radio astronomy are tightly connected to the most important problems of modern astrophysics and the possibility of building more powerful radio telescopes, first of all with better sensitivity and higher angular resolution. Here, it is very important to take into account many specific properties of the radio band. The main features and objectives of studies can be summarized as follows.

(1) The longest wavelengths of the electromagnetic spectrum ($\lambda = 0.1$ mm $-$ 10 km, eight orders of magnitude), the lowest frequencies, and the lowest energy quanta.

(2) The total intensity spectrum of cosmic electromagnetic background radiation reaching the absolute maximum in the radio band coinciding with the maximum of the cosmic microwave background spectrum which lies entirely in the radio band.

(3) The spectrum of spatial fluctuations of the intensity and polarization of the cosmic microwave background tightly related to the parameters of the early Universe, dark matter, and dark energy.

(4) The lowest-temperature objects (from 300 K down to 2.73 K and even to -2.73 K, with gradients as low as 10^{-6} K) studied in the radio band.

(5) Objects with the uppermost brightness temperature (up to 10^{40} K), which is due to the possibility of coherent emission, studied in the radio band.

(6) The scattering of cosmic microwave background radiation from electrons (the Zel'dovich – Sunyaev effect on galaxy clusters) studied in the radio band.

(7) The possibility of studying the interstellar matter of our Galaxy and other galaxies (structure, dynamics, and evolution) probed by the 21-cm line of neutral hydrogen (hyperfine splitting of the ground level), and by lines of other elements and molecules.

(8) Emission from interstellar dust (with observed temperatures down to 7 K and below) studied in the radio band. Dust clouds are transparent for radio waves (the wavelength exceeds the size of the dust grains), hence the possibility of studying the planetary formation processes.

(9) Radio emission of ionized plasma in the continuum and recombination lines (transitions between the uppermost atomic energy levels) in galaxies, the possibility of observing recombination of the Universe, the dark age, the primeval star formation.

(10) The dispersion effect of radio waves propagating in a plasma (measurements of the dispersion measure, DM).

(11) Scintillation of radio sources (turbulence of interplanetary and interstellar plasma).

(12) Measurement of Faraday rotation and Zeeman splitting.

(13) Synchrotron radio radiation from relativistic electrons and the possibility of discovering synchrotron radio emission of relativistic protons (sources of cosmic rays).

(14) Studies of cosmic rays and ultrahigh energy neutrinos: the coherent radio emission generated by high-energy particles impacting a solid body (for example, the Moon) — the Askaryan effect.

(15) Studies of radio emission from supernova shells as possible cosmic ray acceleration sites.

(16) Ultrahigh angular resolution studies into the structure of the vicinity of black holes as possible sites of relativistic particle acceleration (the source Sgr A* in the galactic center, nuclei of other galaxies, radio galaxies, quasars, microquasars, 'superluminous' motion and expansion).

(17) Ultrahigh resolution searches for topological tunnels (wormholes), testing string theory and theories with extra dimensions, studies of observational appearances of the Multiverse.

(18) Radio emission at the plasma frequency and gyrofrequencies: Sun and radio stars.

(19) Studies of the most compact radio sources — pulsars (neutron and quark stars, magnetars, giant pulses), binary pulsars, gravitational wave emission by pulsars.

(20) Masers (brightness temperatures up to 10^{16} K), megamasers, antimasers.

(21) In the radio band, record angular resolution being achieved — up to several dozen microarcseconds (interferometers, multielement arrays, aperture synthesis, multifrequency synthesis). There are prospects for space radio interferometry with angular resolution up to several microarcseconds and even nanoarcseconds, three-dimensional astronomy, interstellar interferometer, the Universe in the near zone.

(22) The most precise coordinate accuracy, proper motions, and parallaxes.

(23) Record brightness-temperature sensitivity (receivers and bolometers taking into the account boundary between quantum and classical statistics, near the maximum of the relic background, being close to realization).

(24) The most accurate timing (nanoseconds, the pulsar time scale).

(25) Low radio wave attenuation allowing studies of the surfaces of planets through cloud layers (Venus) and even subsurface layers (the Moon, with prospects for Mars, etc.).

(26) Coherent radio emission from particles in the magnetosphere of Earth, Jupiter, and, possibly, other planets with strong magnetic fields.

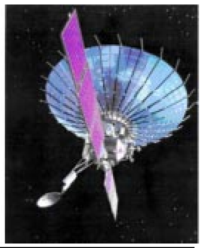
(27) The radio band being optimal for communication with possible extraterrestrial civilizations.

(28) Possibility of building telescopes in the radio band, which observe simultaneously almost the whole sky, and it is very important for studying short-duration phenomena.

(29) In radio astronomy there is the possibility of building telescopes with the largest collecting areas (expenses are inversely proportional to the wavelength).

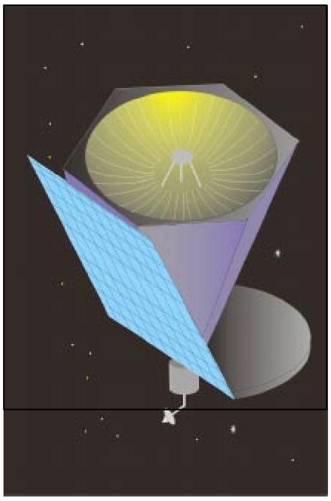
(30) In space there is no technical or atmospheric radio interference (in the submillimeter and millimeter bands, nor for bands below the critical ionospheric frequency). This opens new prospects for the construction of radioastronomical observatories. The absence of the force of gravity is favorable too (only tidal forces remain).

Basic parameters of the RadioAstron mission



Range (λ, cm)	92	18	6.2	1.2 – 1.7
Band width ($\Delta\nu$, MHz)	4	32	32	32
Interference beam width (microarcsec) for the base of 350,000 km	540	106	37	7.1 – 10
Flux sensitivity (σ, mJy), ground based antenna EVLA, 300 s exposition	10	1.3	1.4	3.2

Figure 2. Basic parameters of the Earth – space interferometer (the RadioAstron project).



Antenna diameter 12 m
Spectral range 0.01 – 20 mm

Bolometric sensitivity (wavelength 0.3 mm, 1 h exposition) of 5×10^{-9} Jy (σ)

Sensitivity of the Earth – space interferometer (ALMA) (wavelength 0.5 mm, bandwidth 16 GHz, 300 s exposition) of 10^{-4} Jy (σ)
Interference beam width up to 10^{-9} arcseconds

Figure 3. Basic parameters of the Millimetron project.

The largest radio astronomical space projects providing ultrahigh angular resolution include Earth-space interferometers RadioAstron, designed for observations at centimeter and decimeter wavelengths (basic parameters are shown in Fig. 2 and described in more detail in Ref. [35]), and Millimetron designed for observations in the millimeter and submillimeter ranges (basic parameters are shown in Figs 3 and 4, see Ref. [36] for more detail). The ground-based segment in both cases will include all the world's largest radio telescopes. Both projects are included in the Russian Federal Space Program and are supported by broad international cooperation of research institutes and observatories. New ground-based radio telescopes are under construction. In particular, the Russian Federation, in cooperation with Uzbekistan, is building at the Suffa Plateau the largest millimeter-wavelength radio telescope with a mirror diameter of 70 m [37], the international ALMA (Atakama Large Millimeter Array) consisting of 64 12-m antennas is under construction at an altitude of 5 km in the Atakama desert [38]. The building of the largest multibeam radio (meter and decameter) telescope in Europe, LOFAR (Low Frequency Array), with an effective area of up to million square kilometers [39] has started, as well as the design of the

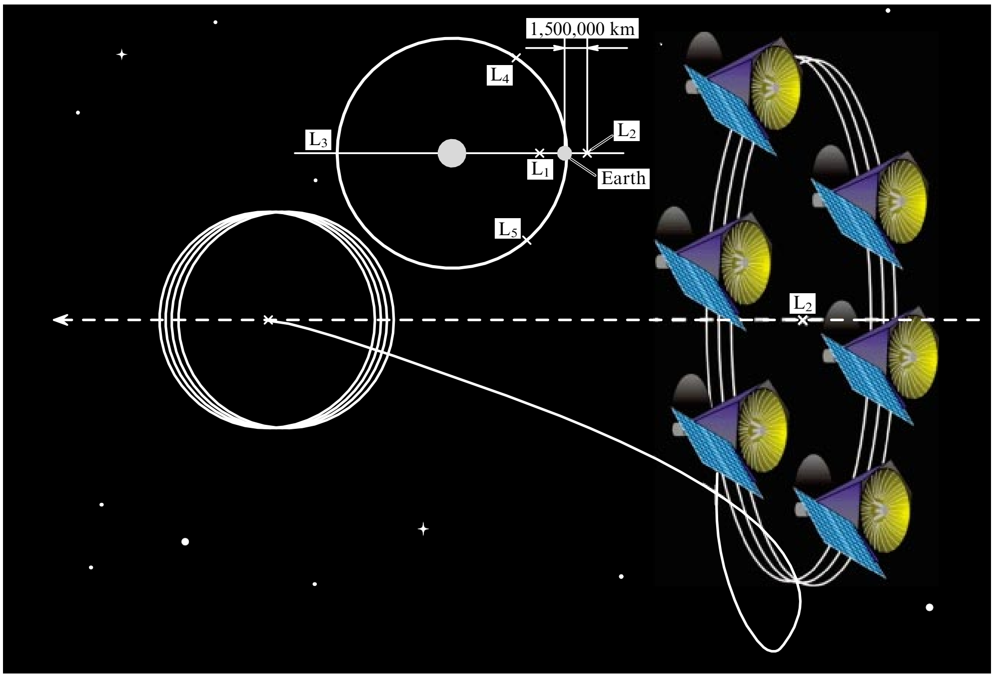


Figure 4. Space multielement interferometer.

centimeter- and decimeter-wavelength SKA (Square Kilometer Array) radio telescope of an equal area [40]. Under preliminary discussion is the construction of new multi-element antenna arrays in space [similar to the scheme of the possible development of the Millimetron project (see Fig. 4)]: in the vicinity of the antisolar Lagrangian point L_2 (1.5×10^6 km from Earth) or even near the 'triangular' points (150×10^6 km). In that case, the entire Universe will fall into the near Fresnel zone for the submillimeter range.

4. Conclusions

The basic problems of astrophysics from the point of view of science at the beginning of the 21st century mainly coincide with the list of astrophysical problems discussed in the book [7, pp. 11 – 74], but I would like to emphasize the importance of reductionism to understand the role of the processes of the origin and evolution of life and information in the Universe.

(1) The highest forms of intelligence in the Universe. The problem of reductionism.

(2) The anthropic principle and the Multiverse.

(3) Topology of the Universe, extra dimensions, wormholes.

(4) The cosmological model and evolution of our Universe.

(5) Dark matter and dark energy.

(6) The beginning of our Universe.

(7) Galactic nuclei and black holes.

(8) Neutron stars, quark and preon stars, origin of cosmic gamma-ray bursts.

(9) Planetary systems and condensed matter in the Universe, origin and evolution of life.

(10) Gravitational wave astrophysics and relic gravitational waves.

(11) Neutrino astrophysics and relic neutrinos.

(12) Origin of cosmic rays.

Radio astronomy has brilliant prospects for solving these issues based on the theory of propagation and generation of radio waves in cosmic media, the physics of cosmic rays and other fields of physics and astrophysics, many of which were elaborated by V L Ginzburg. In conclusion, I would like to deeply thank him for discussions of the problems mentioned here.

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On the origin of galactic cosmic rays

V S Ptuskin

1. Introduction

Our Galaxy is filled with cosmic rays — that is, a gas consisting of relativistic protons, electrons, and atomic nuclei. Most of these particles were accelerated in supernova remnants and wander in the interstellar magnetic fields over several dozen million years before exiting into intergalactic space. The energy spectrum of cosmic rays has a power-law form with a break (a knee) at 3×10^{15} eV (Fig. 1). The maximum detected energy exceeds 10^{20} eV. With a tiny number density of particles, $N \sim 10^{-10}$ cm^{-3}, which is 10 orders of magnitude smaller than the average interstellar gas density in the galactic disk, $n \sim 1$ cm^{-3}, cosmic rays have the energy density $w_{\rm cr} = 1.5$ eV cm^{-3}, which is comparable to the energy density of galactic magnetic fields and the energy density of turbulent interstellar gas motions. Cosmic

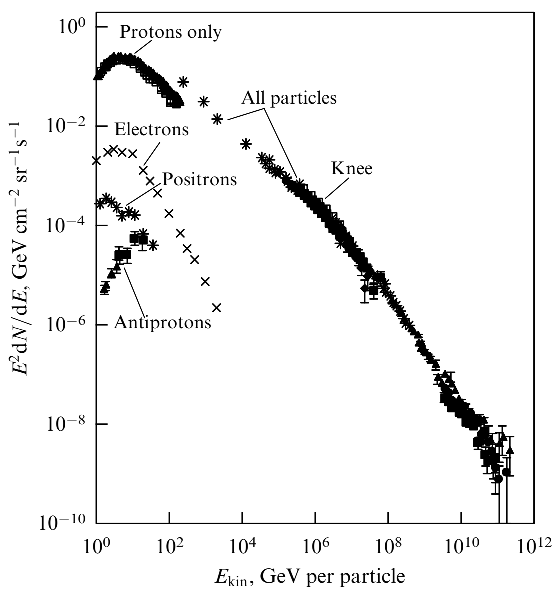

Figure 1. Cosmic ray spectrum with energies exceeding 1 GeV. (Simplified version of the figure from paper [1], where references to the corresponding experiments can be found.)