State-of-Art Challenges and Prospects of Astronomy in Russia

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Abstract. Views on the current state of astrophysical research in Russia against the background of the most important challenges and new world-class projects are presented. The main priorities in the field of astronomical infrastructure development are listed. It is proposed to formulate and implement the Federal Scientific and Technical Program on Astronomy, that will allow us in the current decade to eliminate the existing lag behind the leading scientifically states.

Keywords: astronomy in Russia; telescopes
DOI:10.26119/978-5-6045062-0-2_2020_xv

1 Introduction

The created abundance of modern technical facilities for astronomical research is accompanied by many important results and discoveries that change our understanding of the Universe. The three long-familiar to us observation windows—electromagnetic radiation, cosmic rays and neutrinos—are supplemented by a gravitational window. This made it possible, in a short period of time on a historical scale to build a map of the background radiation with a resolution of 5 arc minutes, to detect the accelerated expansion of the Universe due to dark energy, to detect gravitational waves from the merger of a pair of black holes, to obtain an image of the shadow of a black hole in the center of the giant galaxy M87 and to detect thousands of planets around other stars. Work on the creation of new mega-science class instruments continues throughout the world. Among them are the European project of the EELT telescope with a 39-m mirror in Chile, the 50-meter Mexican-American LMT telescope for the wavelength range 0.8–4 mm, the JWST space telescope to be launched at L2 in 2021, the giant LSST survey telescope with 3-gigapixel camera. The next step is also a network of SKA radio telescopes, an improved LISA interferometer as a development of the LIGO gravitational telescope, CHEOPS (NASA), PLATO (ESA) and ARIEL (ESA) space telescopes for determining the masses and sizes of exoplanets, the WFIRST space survey telescope and many others.

In our country, successful large-scale projects are the creation of the Quasar VLBI Network with ultra-large bases for the task of coordinate-time support, the RADIOASTRON space interferometer of the meter range (the mission was completed in 2019) and the SPEKTR-RG space telescope for studying the Universe in the X-ray range (launched in 2019). Two years ago, construction began on a heliogeophysical complex (NHGC) near Irkutsk, which is designed to study solar-terrestrial relations and the Earth's upper atmosphere. Opportunities for studying neutrino fluxes are expanding at the Baksan Observatory and at the underwater observatory on Lake Baikal.

At the same time, the country's main ground-based observatories - the Central Astronomical Observatory of the Russian Academy of Sciences at Pulkovo, the Crimean Astrophysical Observatory of the Russian Academy of Sciences and the Special Astrophysical Observatory of the Russian Academy of Sciences–are gradually losing their importance against the background of the newest world centers. Our largest optical instrument, the BTA telescope, was built almost half a century ago. The range of scientific tasks that formed during the laying of the observatories remains largely unchanged. Unfortunately we failed to implement the program of Russia's accession to the European Southern Observatory (ESO), which would have allowed us to abruptly overcome the existing technological gap from the scientifically advanced countries. Prospects of construction of a 4-meter class wide field (FoV 2–3 sq. degrees) survey telescope, which was proposed by several observatories five years ago are unclear. Moreover, the outflow of young specialists, which began in the 90s of the last century, led to a gradual aging of teams.

For these reasons, the identification of development priorities is of paramount importance for the future of Russian astronomy. It is important to develop those areas where we traditionally have established schools and tools. These include theoretical aspects of the physics of the early Universe, the study of the properties of relativistic objects, the physics of cosmic rays and neutrinos, and other problems. A hot topic is cold dark matter, which can be studied from dwarf galaxies and galaxies with low surface brightness, the stellar rotation curves of galaxies, and also through studies of the oldest stars in our Galaxy and other galaxies. Ground support for the SPEKTR-RG space mission, which will provide millions of new sources, is also of great importance. Among them there may be objects of a new nature. An interesting task can be the study of short radio bursts with a duration of up to 1 ms–this problem can be studied both with radio telescopes and large optical telescopes in order to detect the corresponding optical sources.

In the next 10–20 years, much attention will be paid to the study of already known exoplanets and to the search for new ones. However, taking into account the current and planned space missions, the principle “the more the better” is no longer applicable here. Most likely, astronomy will focus on a detailed study of the most interesting planetary systems, such as the rocky planets Kepler-62e and Kepler-62f, or a possible system around the Tabby star which displays unusual light fluctuations.

Millimeter astronomy, especially interferometry in the mm range, should become an important area of work. Here we have experience gained by teams in the course of work on centimeter waves. In addition, due to the lack of high-mountainous regions suitable for this observation range on the territory of Russia, we are “doomed” to international cooperation and will, if necessary, be included in international networks.

It is important to continue the development of cosmic ray and neutrino astrophysics in our country. Perhaps we should enter into international cooperation to create a network of Cherenkov telescopes and build such an observatory in one of the country’s high mountain regions.

Astronomy is a fundamental science. And at the same time, it has played, is playing and will continue to play a huge role in solving practical problems facing humanity. In addition to the already mentioned coordinate-time support, the need for astronomical methods to solve the problems of studying and parrying space threats, creating an effective service for the sun, etc. only increases every year. In the second half of the 20th century and early 21st century, humanity faced serious manifestations of space hazards, the most topical problem among which is space debris. Specialists in space activities deal with it every day and fully realize it. An ever-increasing focus is also made on the unpredictable behavior of our main star, the Sun, and the so-called space weather. The asteroid–comet hazard counts as the most catastrophic in scale.

In these and many other projects today it is important to follow the most important principle: to build your programs on the close cooperation with international teams and with a focus on the most ambitious technological capabilities.

2 The Most Important Astronomical Discoveries of Our Era

Scientific and technical progress (the beginning of the space era, the development of ground-based observational facilities, the growth of computing power) led to the rapid development of astronomy and, as a result, to numerous revolutionary discoveries. Astronomy is experiencing its golden era, it becomes the main science that changes the human mind about the structure of the world. In order to feel the scale of the results obtained by the current generation of astrophysicists, it is enough to list the most important of them:

- Discovery of quasars in the early 60-th and the explanation of their enormous luminosity by a gas accretion on a super-massive black hole.
- Discovery of collapsed neutron stars—pulsars, the remnants of supernovae.
- Discovery of the cosmic microwave background radiation in 1964 followed by the space-based full-sky mapping with NASA's Cosmic Background Explorer mission, Wilkinson Microwave Anisotropy Probe, and the European Space Agency's Planck telescope, showing the highest precision picture of the microwave background yet.
- Conclusion about the existence of a hypothetical Dark Matter and the development of ideas what it might be and where it could be.
- Conclusion about the accelerating Universe caused by the Dark Energy—result of the Supernova Cosmology Project.
- First direct observations of the ripples of gravitation waves with the Laser Interferometer Gravitational-wave Observatory LIGO.
- Discovery of the first planet orbiting a main-sequence star followed by thousands new confirmed exoplanets discovered by ground and space-based telescopes.
- Direct measurement of the mass of a black hole in the center of our Galaxy and imaging of the supermassive black hole silhouette in the center of the elliptical galaxy M87.
- Exiting discoveries made by spacecraft exploration of the Solar System.

3 Modern Instrumental Base as a Result of International Cooperation

The role of international cooperation in the field of astrophysical research is very important. On one hand, the ever increasing complexity and cost of research equipment requires the joining of efforts of several countries or agencies for its implementation. On the other hand, new possibilities and ways of researching unique phenomena in the Universe are opening up.

In the field of space research, international cooperation is traditionally at a high level—a significant part of scientific space missions is carried out with varying degrees of international cooperation. The European Space Agency, an international organization created in 1975 for the purpose of space exploration, includes 22 European member countries, and Canada also participates in some projects. Since its inception in 1958, international cooperation has played an important role in NASA's activities - more than two-thirds of NASA's scientific missions have foreign partners. As an example of international cooperation in space, one should mention the International Space Station, an international project of 14 countries. All modern Russian scientific space missions are also being prepared or carried out with varying degrees of foreign participation.

The implementation of complex and expensive instruments for ground-based astronomy also requires the wide cooperation of many participants. A striking result of international cooperation in astrophysics is the first detection of gravitation waves from the merging black holes in 2015. Over one thousand scientists from 15 countries and almost 100 universities took part in the LIGO/VIRGO experiment. Russian scientists also participated in the experiment: the group of V.B. Braginsky from the Moscow State University studied principal noise limitations for the LIGO antennas, while the group of A. M. Sergeev from the Applied Physics Institute in Nizhnij Novgorod provided Faraday rotators in the laser beam of the interferometer.

The largest international organization for ground-based astronomical research is the European Southern Observatory (ESO) established in 1962. The observatory has a unique and most advanced observing technology in the world, worth billions of euros, located in the highlands of the Andes, Chile—in places with the world's best astronomical climate. In addition to fundamental research, the objectives of the observatory include the development and creation of new telescopes and observatories for European astronomers. At present, the ESO includes 15 European countries. Each member country pays entrance and annual fees, the size of which is determined by the aggregate gross product of the state. Observational time on telescopes of the observatory is allocated by scientific committees taking into account the share in the ESO fund. The Program Committee annually considers over 2000 scientific applications for all ESO instruments. Telescope observations are carried out over the world network directly from European institutes and universities. Among the main instruments of the VLT (Very Large Telescope) Observatory is a group of four telescopes with thin mirrors 8.2 m in diameter, built on the basis of the most modern technologies and capable of operating both separately and as a single interferometric complex. The largest ESO project of the current decade is the Atacama Large Millimeter Array (ALMA), consisting of 66 antennae with a diameter of 12 m and 7 m, located at a base 16 km long. The individual telescopes are connected into a network, which is essentially one giant telescope that studies the sky in an atmospheric transparency window from 0.3 mm to 10 mm. The third mega-project of ESO is the construction of an extremely large optical telescope of the future generation ELT (European Extremely Large Telescope) with a segmented 39-meter main mirror. This revolutionary telescope is expected to see the first light in 2025. Its final cost will probably exceed 1.5 billion euro.

The SKA (Square Kilometer Array) project is an international project to create a giant radio telescope with a total collecting area of about one square kilometer. It is assumed that the sensitivity of this radio telescope will exceed existing instruments by 10-100 times. The project brings together the efforts of 12 countries. The key scientific tasks of SKA are: 1) evolution of galaxies, cosmology, dark energy, 2) studies of gravity using pulsars and black holes, 3) the nature of cosmic magnetism, 4) the problem of the formation of the first stars and black holes, 5) issues of the origin of life in the Universe, 6) fundamentally new discoveries that cannot be predicted. The SKA radio telescope will consist of three groups of independent united by a common ideology instruments that differ in the operating wavelength range and the detectors used. The Phase 1 of the creation of SKA involves the construction of approximately 10% of the total planned collecting area. It includes the construction of mid-SKA and low-SKA radio telescopes designed to operate in the middle and low frequency radio bands. The mid-SKA radio telescope is being built in South Africa and will consist of 200 fully rotating antennas with a diameter of 13.5 m each. In parallel, a low-frequency low-SKA is being created in Australia, which will operate in the range of several hundred MHz. This system will consist of about 500 stations, each of which will bring together about 250 individual frequency detectors. Both instruments will position the antennae within a compact center section and several arms that spiral out hundreds of kilometers. The commissioning of the first phase is scheduled for 2022–025. After that, construction of phase two will begin, bringing the collecting area to 100%.

Another example of a new multinational project is the Cherenkov Telescope Array (CTA), the next generation of ground-based instruments for detection of high-energy gamma rays (from 20 GeV to 300 TeV). CTA is designed to detect high-energy particles by observing atmospheric showers over almost all night sky with more than 100 optical telescopes located in the northern and southern hemispheres. On June 1, 2020, scientists from the CTA Consortium announced the detection of gamma rays from the Crab Nebula using a prototype telescope proposed for CTA at the base of Mt. Hopkins in Amado, Arizona. To date, the first CTA telescopes are being installed in Chili (ESO) and at La Palma. The project is being developed and created by the international community of scientists at the initiative of European organizations. It is included in the long-term plan of the European Strategy Forum on Research Infrastructures (ESFRI), the European Astroparticle Physics ASPERA and the ASTRONET European Astrophysics Network.

A high degree of international cooperation is usual for research in the field of neutrino astronomy. The Global Neutrino Network (GNN), created in 2013, which is the first step towards the creation of the Global Neutrino Observatory, unites the largest international neutrino collaborations. Their principle target of GNN are the high-energy neutrinos born outside the Solar system. Each of the next-generation neutrino telescopes, planned and currently being built (Antares, IceCube, Baikal NT1000, KM3NeT), has certain advantages and disadvantages due to its location, as well as the ability to modify the configuration and increase the luminosity of the telescope. The Baikal telescope NT1000 and the Mediterranean KM3NeT, located in the northern hemisphere, and the IceCube detector at the South Pole, due to their geographic location will complement each other and form a worldwide network of installations aimed at finding and studying neutrino sources throughout the entire celestial sphere.

Thus, all ambitious projects for the study of space objects are currently being carried out in international cooperation, and one can hardly expect breakthrough scientific results and world-class discoveries in a single country in isolation from the international community. Russia is unevenly involved in major international infrastructure projects. We actively cooperate with the world's leading organizations in neutrino research, as well as in the field of nuclear research (mainly through the Kurchatov Institute). However, in new projects of optical, infrared, millimeter and radio astronomy, we are passive observers. To make up for this failure, the logical decision for Russia would be to join international consortia.

4 State of Art of Astronomical Research in Russia

4.1 Institutions and Personnel

In total, there are 33 astronomical institutions and university divisions in Russia. They all have two organizational and legal forms: Federal State Budgetary Institution of Science or a subdivision (astronomical department, laboratory, observatory, institute) of the Federal State Budgetary Educational Institution of Higher Education (universities). With the exception of Moscow State University and St. Petersburg State University, all institutions conducting astronomical research are subordinate to the Ministry of Science and Higher Education.

The total number of astronomers in our country is about 1300, 260 of them have a doctorate degree, and 465 people with a Ph.D. The real number is slightly higher, since many researchers work in the field of astronomy not constantly.

There are about 11.3 thousand professional astronomers with a fairly high international rating (members of the International Astronomical Union—IAU) in the world, about a quarter of them work in the United States. In Russia, there are 420 members of IAU (approximately 3 IAU members per 1 million inhabitants). The share of IAU members in Russia does not exceed 30% of the total number of astronomers in the country, which is determined by the level of Russia's annual contribution to the IAU. For developed countries, the typical proportion is from 7 to 15 members of the IAU per 1 million inhabitants. Note that more than half of professional astronomers are members of the IAU. On average, a Russian astronomer publishes slightly more than 1 paper per year in a peer-reviewed journal. Each article is cited on average once per year. The reason for the low citation rate is the relatively low rating of Russian journals.

The "basic" budgets of astronomical institutions in Russia, as a rule, are almost entirely spent on salaries, utilities, and occasional small business trips. "Infrastructure" expenses for the maintenance and development of astronomical instruments are made from "off-base" budgetary financial instruments, such as: Federal Target Programs (FTP), Programs of the Russian Academy of Sciences (RAS) and the Ministry of Education and Science, grants from state scientific funds, mainly the Russian Foundation for Basic Research (RFBR) and the Russian Science Foundation (RSF). "Additional" funding is determined by the volume of work carried out mainly on space projects from the funds of ROSCOSMOS contracts and on applied projects, under contracts with interested ministries and departments, as well as grants from non-state funds.

The total annual budget of Russian astronomy is equal to the sum of all the budgets of astronomical institutions, taking into account the above components. The "basic" budget for 2014 was 1323 million roubles, the "off-base" part was 460 million roubles. "Additional" financing is estimated at up to 50% of the amount of the basic and non-basic parts. One astronomer researcher per year in Russia spends about 1 million roubles (corresponds to 10 thousand USD), which is much less than in the United States. This disparity is due not so much to the difference in salaries (several times), as to the difference in the costs of technology and research support.

4.2 Ground-Based Research Infrastructure

Of the 33 astronomical institutions mentioned above, 28 have their own instrument base for astronomical observations. These are optical telescopes, radio telescopes, polygons, special equipment complexes, etc. There are 25 objects with the USE status (Unique Scientific Equipment), 10 infrastructure facilities are Shared Use Centers (CCC). At first glance, this is a lot, however all the listed tools are not unique in fact. Even the largest Russian telescope, the 6 m optical BTA telescope, in terms of its parameters, has already come out of the twenty best instruments in the world, although in the end of 70-ties it was ranked at the first position in this list. Among optical telescopes with an aperture larger than 2 m are the 2.6-m telescope of the Crimean Astrophysical Observatory of the Russian Academy of Sciences, the 2.5-m telescope of the Kislovodsk Observatory of the Moscow State University, and the 2-m Zeiss telescope of the joint Russian-Ukrainian observatory at Terskol peak. Three telescopes with 1.5-m mirrors and the same number of 1-m instruments can be added to this list. There are also two networks of small-aperture (50 cm) telescopes. In astrophysics the most productive is the MASTER robotic network (Moscow State University), the main task of which is to observe the sources of gamma-ray bursts. MASTER-II is very fast positioning alert, follow up and survey twin telescopes global network with own real-time auto-detection software. MASTER goal is One Sky in One Night up to 20–21^m. The International Scientific Optical Network (ISON) maintained by the Keldysh Institute of Applied Mathematics is mainly designed to record space debris using 50- to 70-cm telescopes. The total area of the mirrors of Russian optical telescopes is about 42 square meters, which is only 2% of the area of the mirrors of optical telescopes in the world. After the commissioning of new giants, EELT, MMT, JWST, GST and others, this share will fall below 1%.

In general, we can say that the optical observational astronomy of Russia is massively represented by instruments created during the USSR period in accordance with the tasks and technical capabilities of that time. Today there are several large observatories that conduct systematic observations of space objects according to planned scientific programs. Most telescopes are designs with complex operational characteristics and infrastructure, the ergonomic costs of which could be minimized through upgrades.

A similar picture is observed with ground-based Russian radio telescopes intended for astronomical research. The largest Russian radio telescope RATAN-600 with the 600 m variable profile ring antenna, the 22 m parabolic reflectors RT-22 in Crimea and in Pushchino Radioastronomical Observatory, the cross-shape antenna DKR-100 and BSA antenna array for pulsars study in Pushchino are able to solve a wide range of problems at cm wavelengths, however, today they are not participants in the breakthrough research. The list can be expanded with two large 70 m antennas in Medvezhi Ozera and Kaliazino, which are periodically used by astronomers from the Astro Space Centre of the Lebedev Physical Institute of the Russian Academy of Sciences. Another unique radio instrument is the Siberian Solar Radio Telescope (SSRT)—a cross-shape radio interferometer built in the middle 80th. It stands somewhat apart from other radio instruments because its only target is the solar atmosphere seen at microwave frequencies (5.7 GHz). This instrument is currently being modernized as part of the program for creating a new heliogeophysical complex—its base and spatial resolution are increasing and the frequency range is expanding. The radio interferometric Quasar complex, built in the last two decades, is used mainly for coordinate-time support of the country. However, from time to time it is used for astrophysical observations too.

Today in Russia there is no instrument for the microwave astronomy, just as there is no suitable site for installing telescopes of this range. However, when creating such an instrument, it is necessary to compare its planned characteristics with the already realized characteristics of ALMA, the largest ESO facility located on the Chajnantor plateau, 5000 m altitude in northern Chile. ALMA provides continuum and spectral-line interferometric imaging for wavelengths from 0.32 mm to 3.6 mm, and angular resolution up to 5 milliarcsec. Following the ALMA Development Road Map, its science drivers will be:

- tracing the cosmic evolution of key elements from the first galaxies through the peak of star formation in the Universe;
- tracing the evolution from simple to complex organic molecules through the process of star and planet formation down to solar system scales;
- imaging of protoplanetary disks in nearby star formation regions to resolve their Earth-forming zones.

Summarizing the above, it can be argued that the list of research methods that can be implemented with the available tools is rather limited. So, in the Russian Federation there are no methods of adaptive optics, there are no observations in the infrared and millimeter range, the use of the radio interferometry method is limited. This means that the Russian Federation cannot fully participate in large international projects in a number of areas of research—from objects of the Solar System to supermassive black holes.

4.3 Space Astronomy

Despite the fact that the topic of the review is ground-based astronomy, let us dwell briefly on the state of affairs in the space science field.

In January 2019, the radio interferometric observatory RADIOASTRON stopped operating. It managed to detect the extreme brightness of quasars, which can be caused by proton jets—sources of high-energy neutrinos. From the maser emission, RADIOASTRON has discovered ultra-compact regions of water vapour in the disks of galaxies. It also observed the speckle structure of radio emission from pulsars scattered by the interstellar medium.

The only Russian observatory currently operating in space is Spectr-RG, which has completed the construction of the second of eight maps of the entire sky in the X-ray range using Russian and German telescopes ART-XC and eROSITA. The most important task for the next few years will be to support this space mission using ground-based optical observatories.

The planned Federal Space Program for the period 2021-2025 suffers from reduced funding of the scientific part of the Program. For the period 2016-2022, the sequestration of the scientific part of the Program will be 35% (the sequestration of the entire Federal Space Program is 16%). With the minimum 15 billion rubles, annually required to support the planned science missions, only 2.9 billion is planned for 2023, which practically means the curtailment of the scientific program. Only two Roscosmos programs are provided with funds, Luna-25 (2021) and ExoMars (2022, in cooperation with ESA). Without an increase in funding, the planned launch of the Spektr-UF ultraviolet telescope in 2025 will be postponed for several years. The launch of the Spektr-M microwave-range telescope into space is transferred beyond the “event horizon” (after 2030). Most likely, the main attention of the scientific part of the Federal Space Program will be focused on the lunar direction, the fundamental scientific significance of which is not so evident.

Summing up, it can be argued that despite some world-class achievements in the development of space experiments technologies, in general, the Russian Federation is significantly inferior in this aspect to the leading space powers and agencies. Suffice it to say that our spending on scientific space is 1/60 of that of the United States.

4.4 The Highlights

Soviet and Russian scientists made significant contributions to world astrophysics. The most significant achievements of the world level include:

Sunyaev-Zeldovich effect. The theory developed by well-known Soviet astrophysicists in the 60s–70s of the last century claims that the relic radiation in space is gradually scattered under the influence of electrons. Over the past decades, it has turned from a beautiful theoretical idea into one of the most productive methods of observational cosmology, opening up the possibility of determining the main cosmological parameters, including determining the role of ”dark energy” in the Universe and directly measuring the Hubble constant.

The Shakura-Sunyaev’s theory of accretion disks. The article by Shakura and Sunyaev (1973) on the theory of accretion is the most cited work in the world of theoretical astrophysics (5870 references according to NASA ADS) and one of the most cited (among almost three million works) articles in modern astrophysics. The theory developed by them has long been generally accepted when describing the transfer of matter and energy release in close binary systems and during accretion onto supermassive black holes. The same theory applies to the description of protoplanetary disks.

The theory of an inflationary universe. The hypothesis about the physical state and the law of expansion of the Universe at the early stage of the Big Bang, which assumes the period of the expansion accelerated in comparison with the standard model of the hot Universe. 1970s. A key contribution to this theory was made by Soviet and ex-Soviet astrophysicists A. A. Starobinsky and others.

The three-dimensional structure and motions of galaxies in the Local Universe. Astronomers of the SAO (I. D. Karachentsev and others) found that the random motions of galaxies on a scale of several megaparsecs turned out to be much smaller than theoretically expected. It was also shown that gravitationally bound systems contain less than half of all matter in the Universe, both baryonic and dark. As a result, it was possible to determine the parameters of the mass of dark matter in our galaxy cluster. The average density of the substance was also determined. These results made a fundamental contribution to the cosmology of the Local Universe.

The problem of solar neutrino deficiency. Using the gallium-germanium neutrino telescope (Baksan Neutrino Observatory), designed to measure the flux of solar neutrinos, the Russian-American SAGE experiment was the first to demonstrate the existence of a deficit of solar neutrinos in the entire neutrino energy range. Direct evidence of the validity of the Standard Solar Model for solar neutrino oscillations was obtained, and it was shown that the overwhelming majority of solar neutrinos arriving on Earth are low-energy neutrinos from the proton-proton reaction.

The list of the most important achievements can be significantly expanded. Most of them lie in the field of theoretical research and belong to the Soviet period. Today our main task is to develop a plan for the development of astronomical research in the country for the next decade. This year, the Russian Academy of Sciences has developed and sent to the Government of the Russian Federation the Plan of fundamental and exploratory research for 2021–2030. The plan takes into account new trends of modern science: the growth of interdisciplinarity and transdisciplinarity of scientific research, an orientation towards timely identification and responses to “big challenges”, the explosive development of technologies. In accordance with the plan, the priority areas of research in astronomy include almost the entire spectrum of possible problems - from the problems of the origin, structure and evolution of the Universe to the physics of planets of the Solar System. Research methods include X-ray, ultraviolet, optical, infrared, subterrahertz, radio, gravitational, neutrino astronomy, and methods for studying cosmic rays and plasma processes. Obviously, it is necessary to determine priorities from the point of view of the entire Russian astronomical community

5 Priority Projects for Russian Astronomy

Five years ago on the initiative of the RAS, the Scientific Coordination Council under the Federal Agency for Scientific Organizations of Russia, the Ministry of Education and Science, the Office of the President for Scientific and Educational Policy, an interdepartmental working group (WG) of experts in astronomy was formed. The members of the WG were experts in various fields of observational astronomy and astrophysics. The group was instructed to develop an integral Program for the development of a ground-based experimental base for astronomy and astrophysics in Russia, in which the priorities of Russia's participation in large foreign astronomical projects will be logistically and financially coordinated with plans for the development of ground-based astronomical infrastructure. Over 500 astronomers were involved in the discussion. An important part of the process was a comprehensive audit of existing ground-based astronomical facilities in Russia and consideration of the issue of personnel training. Here we would like to draw attention to the main conclusions of the work, since over the past 5 years the situation has practically not changed.

Following the discussion, the leaders among international mega-projects were selected:

- Priority 1: Russia's accession to the European Southern Observatory (ESO);
- Priority 2: Russia's accession to the Square Kilometer Array (SKA) consortium.

Among the mega-projects on the territory of Russia, the following projects were highlighted:

- Priority 1: Project of a 4 m optical telescope with a wide field of view for installation in the Northern Hemisphere;
- Priority 2: Completion of the construction of the 70 m radio telescope on the Suffa plateau (Russian telescope in Uzbekistan);
- TAIGA Cherenkov telescope project for cosmic ray research.

The following projects were selected as national middle class ones:

- Priority 1: Baikal Neutrino Telescope;

– Priority 2:Long-wavelength radio telescope.

In addition to the pure (basic) astronomical projects, three "service" (applied) programs were recommended for co-financing by ministries and agencies:

– Priority 1: Creation of the Russian Sun Service for the study of the sun and its interaction with Earth;
– Priority 2: Creation of scientific ground-based astronomical infrastructure for the ground segment of the Russian system for warning and counteracting space hazards;
– Fundamental and applied coordinate-time support of Russia.

The discussion of the commission's conclusions was held at a high level in the Government of the Russian Federation and in the Administration of the President of the Russian Federation. Common to all discussions was the conclusion about the need to restructure astronomy in the country. The country's leadership proposed, as a condition for the allocation of large funds, a reduction in the number of astronomical organizations through mergers. Such conditions for the Russian astronomical community, weakened by decades of underfunding, turned out to be unacceptable.

6 Action Strategy

The only way to realize the priority goals in the field of astronomical infrastructure is to develop the Federal Scientific and Technical Program, FSTP. There are no uniform requirements for the procedure for approving the FSTP, but common to all such programs is the justification at the Council for Science and Education under the President of the Russian Federation and the publication of the corresponding presidential decree. The documents to be prepared should include an analysis of the state of the art in the scientific area, the tasks and tasks of the FSTP, the main areas of work and activities, the expected results and indicators, the estimated amount of funding. An alternative to the FSTP can be the Comprehensive Research Program, CRP. An example of such a CRP is the program "On the Development of Engineering, Technology and Scientific Research in the Field of Atomic Energy Use in the Russian Federation", approved in 2020. CRP is inherently more oriented towards basic science. Based on the priorities identified by Russian astronomers, the sections of such an FSTP or CRP can be:

1. Russia's accession to the ESO;

2. Construction of a survey robot-telescope with a diameter of 4 m for observations in the spectrum range of 0.4–2.2 microns;
3. Development of the Baikal neutrino telescope for studying high-energy neutrinos;
4. Development of sub-terahertz astronomy and the radio astronomy observatory on Suffa;
5. Creation of a system of survey telescopes of class 0.5 - 1 m for detecting transient sources and creating the basis for a defence system against space hazards;
6. Creation of a center for space instrumentation.

The total expenses for the program will amount to about 50 billion roubles in today's prices. Below we will briefly dwell on each of the projects.

Joining ESO. The history of Russia's accession to the ESO began in 2006 with the visit of the then ESO Director General C. Cesarsky to Moscow. The meeting was attended by the country's leading astronomers. C. Cesarsky invited Russian astronomers to take part in the implementation of new ambitious ESO projects—a giant array of mm-range telescopes and a giant optical telescope OWL (at that time it was planned with a diameter of 100 m). On 26 October 2009 in Moscow, in the Russian Academy of Sciences a meeting was held of the leading Russian scientists and statesmen with the new ESO Director General prof. Tim de Zeeuw and the Head of ESO International Relations Rowena Sirey. In attendance were: the Deputy Minister of Education and Science A. V. Khlunov, the official of the Administration of President of Russia E. V. Popova, the Director General of the Lytkarino Optical Glass Factory A. P. Patrikeev, the head of the Department of Physics and Astronomy of the RAS V.A. Matveev, the head of the Russian Foundation for Basic Research V. Ya. Panchenko, the director of the Astro-Space Centre of the Lebedev Physical Institute of the RAS N. S. Kardashev, academician A. A. Boyarchuk, academician D. A. Varshalovich, director of the Sternberg Astronomical Institute academician A. M. Cherepashchuk and others. The matter under discussion was the possibility of Russia's membership in ESO. In case Russia joins the ESO, the our scientists and industrial enterprises would be open to the following scope of capabilities:

1. An immediate access for Russian astronomers to all of ESO's facilities, including the world-leading VLT and ALMA.
2. Potential collaborations in new technical projects and an access to the state-of-the-art technologies, such as adaptive optics, powerful impulsed lasers, multiprocessor computer systems, detectors for infrared, submillimeter and radio ranges.

3. Potential participation of the Russian optical-mechanical industry in the contemporary innovative projects: in particular, the European ELT telescope with a 39 m segmented mirror. The ESO long term planning will provide for future new facilities after ELT is completed, one possibility for which might be the SKA antenna array with the surface of 1 square kilometer.
4. Access for young Russian astronomers and engineers to job vacancies within the framework of ESO's projects.
5. Political rapprochement between Russia and the Europe by means of the scientific integration.

Joining the ESO was supported as a priority hall at three astronomical conferences in Kazan, Arkhyz and Crimea. In 2011, all members of the Russian Academy working in the field of astrophysics signed a letter to the President of Russia V. V. Putin, in which it was emphasized that Russia's entry into the ESO is the only way for our science to overcome the technical lag that has developed over decades and to join the study of the Universe at the global level in the shortest possible time. The RAS President Y. S. Osipov turned to V. V. Putin with a similar letter, which resulted in the President's order of 2013 No. Pr-1144, paragraph 3 (b).

In the case of Russia's accession to the ESO, our share in the budget of the organization was 9.8%. In 2011, Russia's admission fee was 118 million euros, and the annual contribution was 13.6 million euros. ESO was ready to provide Russia with a 10-year instalment plan for the payment of the entrance fee, as well as to halve the annual fees for a period of several years. However, no decision was made at the government level. The topic remains relevant today, although the economic condition of the country is worse than 10 years ago.

The Baikal Deep-underwater Neutrino Telescope. Baikal-GVD (Gigaton Volume Detector) is one of the world's largest neutrino telescopes. Its first substructure named DUBNA was put into operation in 2015. The DUBNA cluster comprises 192 optical detectors of Cherenkov radiation from generated by neutrino cascades of charged particles. In 2020, up to 8 new strings of photomultiplier arrays will be installed in Baikal providing the total volume about 0.4 cubic km. The instrument will shed light on one of the deepest mysteries of physics: how cosmic particles could be accelerated to extremely high energies and what are the sources of high-energy neutrinos (10 GeV). To complete the instrument, about 4 billion roubles are still needed.

The 4 m survey telescope. The need for a Russian wide-angle survey telescope is clear. It can be used for deep surveying of the northern sky, thus supporting research in the wide range of projects from our Solar System to cosmological targets such as dark matter and dark energy. The telescope should be equipped with a large format CCD mosaic and a low-resolution multi-object spectrograph. The proposal for the creation of such instrument was made by SAO, Pulkovo observatory and GAISH MSU.

Millimeter wavelength astronomy. In 1995, the Intergovernmental Agreement was signed between Russia and Uzbekistan, which provides for the construction of an international radio astronomy observatory on the Suffa plateau in Uzbekistan. The main goal of the project is to complete the construction of a 70 m antenna for operation in all atmospheric windows from 10 mm (30 GHz) to 0.8 mm (375 GHz). Director of the Astro Space Center of the Lebedev Physical Institute, academician N. S. Kardashev considered the RT-70 telescope as a ground element of the MILLIMETRON space interferometer. The construction of RT-70 was repeatedly discussed at meetings of the Intergovernmental Commission of the two countries (the last meeting was held in November 2020). However, despite numerous decisions, work at the observatory has not been carried out for two decades.

To address the microwave astronomy challenges, the Suffa observatory should have outstanding capabilities. In the same time, the absorption of short-wave radiation by water vapours and oxygen at Suffa plateau (2400 m altitude) will significantly limit the possibilities of the instrument. As a result of numerous discussions of the project, which took place with the participation of the former ALMA director prof. Thijs de Graauw, it was decided that the optimal solution would be to install a 15-20 m diameter telescope in parallel with the examination of the 70 m antenna. The second 15-20 m instrument could be installed in Russia (the most probable site is the vicinity of SAO), which will allow realizing the giant baseline interferometric mode providing imaging abilities at an angular resolution of 100 micro-arcseconds. This arrangement will make it possible to use the instruments in the global interferometric network Event Horizon Telescope. The involvement of Chinese and South Korean astronomers in the project will make it possible to create new instruments in a relatively short period of time, about 5 years. Taking into account the development of the cryogenic receivers, hydrogen time standards, correlators and digital systems for data transmission, as well as the training of specialists, the costs of the program can amount to up to 5-7 billion roubles. The cost of completing the 70-m telescope can only be estimated after a comprehensive examination of the project.

Optical Transient Network. In 2020 a dedicated BRICS Flagship programme to develop an extended network of 1-m class ground-based optical telescopes for an all-sky survey to detect short lived optical transients and to allow follow-up of multi-wavelength and multi-messenger transient objects was announced. This major BRICS astronomy project is named OTN (Optical Transient Network). This will leverage existing and planned new facilities within the BRICS countries and will also draw on the opportunities presented by other multi-wavelength space- and ground-based facilities that exist within the BRICS group. Russian Institutes (INASAN, SAO RAS, CrAO) and Chinese Research and Technology Centers (CIOMP, NAO CAS)—are major participants of the OTN Project.

Space research instruments. The need to finance the instrument-making infrastructure of scientific organizations performing space research should be emphasized separately. Due to departmental affiliation, scientific organizations do not have access to the investment program of ROSCOSMOS. The creation of a center for space instrumentation at the Space Research Institute of the Russian Academy of Sciences would significantly reduce the development and manufacture of scientific instruments, as well as improve their quality and reliability.

7 Conclusion

Russian Astronomy is going through difficult times. Previous decades of insufficient attention to our science are affected. Modern world astronomy is developing rapidly, and we must keep up with the pace of this development. We have the ability to do this. But we must make the most of these opportunities in the coming years.

Acknowledgements. The authors are grateful to D. V. Bisikalo, A. M. Cherepashchuk, N. R. Ikhsanov, Y. Y. Kovalev, V. D. Kuznetsov, L. N. and S. F. Likhachev, A. A. Petrukovich, A. N. Rostopchina-Shakhovskaya, R. A. Sunyaev, S. V. Troitsky, V. F. Vdovin, V. V. Vlasyuk, and L. M. Zelenyi for numerous discussions, which, although they did not lead to the development of a common point of view, were extremely useful in shaping our vision of the problem.