# Chapter 3
# The Development of Radio Astronomy at the Sternberg Astronomical Institute of Lomonosov Moscow State University and the Space Research Institute of the USSR Academy of Sciences

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**Abstract** This chapter provides information about the emergence and development of radio astronomy at the Sternberg Astronmical Institute of Moscow State University (GAISH), and further at the Space Research Institute (IKI). The main results of theoretical studies of mechanisms for the Sun, Galactic and extragalactic radio emission and their relationship to physical processes in space are laid out in detail. The results of observations carried out at the initiative of and with the participation of radio astronomers from GAISH and IKI using many radio telescope in the Soviet Union and abroad are also considered, including methods for space radio astronomy.

## 3.1 The Beginning of Radio Astronomy Studies at GAISH. Creation of the Department of Radio Astronomy

The establishment and development of radio astronomy at the Sternberg Astronomical Institute of Lomonosov Moscow State University (GAISH) and the Space Research Institute of the Academy of Sciences (IKI) is inseparably linked to the name of I. S. Shklovskii. The first radio astronomy research of Shklovskii was carried out at the end of the 1940s, when the results of radio observations of the Sun and Galaxy obtained in a number of countries during the period of the Second World War became known. Before this, his scientific interests were associated with classical problems in astrophysics, primarily spectroscopy.

In 1946, Shklovskii investigated mechanisms for the generation of the radio emission of the quiet Sun. This work, together with the work of V. L. Ginzburg and D. Martin, enabled the construction of an isothermal model for the solar atmosphere, which still lies at the basis of the theory of the radio emission of the quiet Sun. This model was used to draw the fundamental conclusion that the sources of solar radio emission are in the outer layers of the solar atmosphere—the chromosphere and corona—and not in the photosphere, with the main contribution to the solar emission at metre wavelengths being made by the corona. This conclusion was brilliantly confirmed by observations during the solar eclipse of May 20, 1947 (see

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Essay 1). Simultaneously, Shklovskii put forth the hypothesis that the radio emission of the "perturbed" Sun was associated with plasma oscillations in the corona, which arose during the passage of flows of particles. This brave hypothesis, based on the closeness of the Langmuir frequency for plasma oscillations in the corona to the frequency of metre-wavelength radio waves, was further developed by V. V. Zheleznyakov (at the Radio Physical Institute in Gorkii), and is one of the main mechanisms lying at the basis of the theory of the radio emission of the perturbed Sun.

Shklovskii's monograph *The Solar Corona* (Moscow, Leningrad: Gostekhizdat, 1951) came out in 1951. The theory of the radio emission of the solar corona was developed by Shklovskii in close connection with problems associated with optical spectroscopy of the corona. This led to the hypothesis that the solar corona was ionised, and the basis of modern concepts of the hot corona. The idea that the corona is hot now seems completely obvious, but, in the 1950s, this concept had to be defended in a very stubborn struggle with adherents of the theory that the corona was cool. Based on his ionisation theory, Shkovskii determined the chemical composition of the solar corona and predicted the existence of hard electromagnetic radiation from the Sun.

Among works related to solar radio astronomy, we should mention the important research of Shklovskii and S. B. Pikel'ner at the beginning of the 1950s on the radio brightness distribution over the disk of the Sun. They showed that an enhancement in the brightness of the disk toward the limb should be expected at decimetre wavelengths, in contrast to the well known limb darkening observed in the optical. This predicted effect was confirmed observationally. The refraction of low-frequency radio waves in the corona was studied In the process of these investigations.

Shklovskii also made a fundamental contribution to the development of Galactic radio astronomy. In 1948, after van de Hulst had published his paper suggesting the fundamental possibility of observing the 21-cm radio line of hydrogen, Shklovskii carried out the necessary calculations of the transition probability for this line and the expected intensity of Galactic radio emission at the corresponding frequency. He showed that the detection of the line should be possible with the observational equipment available at that time. In 1951, the 21-cm radio line of hydrogen was detected nearly simultaneously in the USA, England and Australia.

Over the next several years (1948–1953), Shklovskii conducted a number of studies in which the foundations of radio spectroscopy of the Galaxy were laid. First and foremost, he considered the radio line of deuterium at 91.6 cm, as well as two radio lines of nitrogen at 15 and 30 m wavelength with negligibly small transition probabilities. Attempts to detect these lines have thus far not yielded clear results. Shklovskii then arrived at the fundamentally important conclusion that it should be possible to observe radio lines of interstellar molecules. He calculated the frequency and intensity of the 18-cm hydroxyl line. At that time, the available observational equipment was not able to detect this line, and it was finally detected only in 1963.

This discovery had huge importance, since cosmic maser emission at the frequency of the hydroxyl (OH) line was soon detected, and the sources of this maser emission turned out to be closely associated with star-formation processes (which was first indicated by Shklovskii in 1966). Together with his hydroxyl calculations, Shklovskii performed calculations for the CH line at 9.45 cm, which proved to be very weak, and was detected only in 1973. Soon after this discovery came a period of vigorous blossoming of molecular radio spectroscopy, which became one of the most important areas in radio astronomy.

At the beginning of the 1950s, Shklovskii carried out a series of theoretical studies on the thermal radio emission of the Galaxy. He proposed to observe such thermal radio sources (H II regions) on the radio telescopes of the Crimean Station of the Lebedev Physical Institute (FIAN), but the sensitivity of the available equipment was insufficient to realise this idea. Further, such observations were carried out successfully at the Kaluga Station of FIAN (see Essay 1).

Shklovskii's studies of the nature of the non-thermal radio emission of the Galaxy proved to be more fruitful. In 1952, he predicted the presence of a spherical component to the Galactic radio emission, which formed a so-called Galactic corona. A detailed theory of the radio corona of the Galaxy was developed by Pikel'ner and Shklovskii in 1957. The detection of the radio corona played a large role in the understanding of the mechanisms generating the non-thermal radio emission of the Galaxy, since it disproved the hypothesis that this emission was associated with "radio stars." Subsequent, more modern observations showed that the Galactic corona does not make as large a contribution to the overall radio emission of the Galaxy as was first proposed by Shklovskii.

Shklovskii actively took part in laying the basis for and applying the theory of radio synchrotron radiation. The idea that the non-thermal component of the cosmic radio emission was radiation by relativistic electrons in weak magnetic fields was expressed in 1950 by K. Kipenheuer, H. Alfven and N. Herlofson. In the early 1950s, a quantitative theory of synchrotron radiation was developed in the works of Ginzburg and his students and collaborators (I. S. Syrovatskii, A. A. Korchak, G. G. Getmantsev, V. A. Razin). In Shklovskii's view, a serious difficulty in applying this theory to the non-thermal radio emission of the Galaxy was the fact that (as it seemed at that time) the magnetic fields should be associated with clouds of interstellar gas, which lie in the Galactic plane, while the non-thermal radio emission seemed to be coming from a spherical system. However, after Pikel'ner showed in 1952 that the magnetic field is not localised only in interstellar clouds, but also in the intercloud medium, this difficulty was removed. Already in 1953, Shklovskii turned from the radio-star theory, which he had previously supported, and actively took part in the development of the theory of synchrotron radiation, concentrating his efforts on possible astronomical manifestations of the synchrotron mechanism. First and foremost, he invoked this mechanism to explain the radio emission of the Galactic corona, and showed that this corona can be treated like a reflection of the distribution of the electron component of cosmic rays. However, the question of the origin of the cosmic rays then arose.

In 1953, Shklovskii applied the synchrotron theory to estimate the energetics of supernova remnants. He showed that each supernova explosion gave rise to relativistic particles with a total energy of about $10^{41}$ Joules (about $10^{48}$ ergs). To estimate the efficiency of this process in generating cosmic rays, it was necessary to know the supernova rate in the Galaxy. Shklovskii's interest in historical chronicals making reference to supernovae dates to this time. He was the first radio astronomer to turn attention to a number of supernovae (such as the supernova of 185 in Centaurus, the supernova of 1006 in Lupus and others), and proposed to search for radio sources at the locations of these supernovae, which were indeed detected. By using data on supernovae referred to in historical chronicles, Shklovskii was able to increase previous estimates of the supernova rate by nearly an order of magnitude. It turned out that supernova explosions can fully compensate the decrease in the energy of cosmic rays due to nuclear collisions.

Very important studies of Shklovskii concerning the nature of the emission of the Crab Nebula occurred in this same period. At the beginning of 1953, he explained the radio emission of the Crab Nebula as being due to the synchrotron mechanism. However, the nature of the optical radiation remained unclear. The proposed theory of R. Minkowski that this was thermal radiation associated with free–free transitions encountered great difficulties. Shklovskii approached this problem from a completely unexpected direction: if the radio emission of the Crab Nebula was not a continuation of its thermal optical emission, might the optical continuum of the nebula represent a continuation of the radio synchrotron radiation to the optical? Subsequent calculations fully supported this insightful guess. Thus, Shklovskii was the first to develop the concept that there was a single radiation mechanism acting from the optical to the radio. The prediction of I. M. Gordon based on this theory that the Crab Nebula radiation should be appreciably polarised was soon confirmed observationally by the Soviet astronomers M. A. Bashakidze and V. A. Dombrovskii. Shklovskii's studies of the nature of the radiation of the Crab Nebula gave a push to the wide application of the synchrotron mechanism to other astrophysical objects.

Shklovskii's book *Radio Astronomy* came out in 1953 (Moscow: Gostekhizdat, 1953). Although formally this was considered to be a popular-science book, the main methods and achievements of radio astronomy at that time were laid out at a high scientific level. The book became an indispensible aid for many beginning radio astronomers.

In 1953–1954, Shklovskii gave the first course in radio astronomy in the Soviet Union in the Astronomy Department of Moscow State University, which was attended not only by students, but also by researchers at a number of institutes in Moscow who were starting to work in radio astronomy. A student seminar on radio astronomy under the direction of Shklovskii and A. E. Salomonovich (Shklovskii led the theoretical part of the seminar and Salomonovich the experimental part) was also organised in the Astronomy Department. This seminar, in which radio physicists and astronomers took part, was a very good school; by representing different approaches to radio astronomy (by astronomers and radio physicists), it facilitated understanding between the various types of scientists involved. The first participants in the seminar included such now well known radio astronomers as Yu. N. Pariiskii, N. S. Kardashev and N. S. Soboleva. Thus, fertile ground for the serious development of radio astronomy studies was created at the Sternberg Astronomical Institute.

The work of Shklovskii led to the development at GAISH of a new research direction—radio astronomy. A group of young astrophysicists specialising in radio astronomy formed around the scientist. Precisely this group formed the basis for the Department of Radio Astronomy formed at GAISH in 1953 under the supervision of Shklovskii. The first employees of the department were B. M. Chikhachev, who was at GAISH part time (his main work was at FIAN) and the fourth-year student in the Faculty of Mechanics and Mathematics of Moscow State University N. S. Kardashev. In 1953, V. N. Panovkin was accepted as a PhD student in radio astronomy under Shklovskii (his second supervisor was V. V. Vitkevich), with P. V. Shcheglov following a year later, in 1954. Also in 1954, Kardashev took part in the work of the Kaluga Station of FIAN under the supervision of N. L. Kaidanovskii, carrying out studies on the detection of discrete radio sources at 3 cm. These were the first observations of thermal nebulae at very short (for that time) radio wavelengths, and led to the detection of thermal radio emission associated with free–free transitions from diffuse gaseous nebulae (see Essay 1).

The development of radio astronomy investigations at GAISH required the establishment of an experimental base. With this goal in mind, an engineering group was formed in the Department of Radio Astronomy, and work was begun on the development of equipment, first and foremost a radiometer designed to operate at a wavelength of 21 cm (for both line and continuum observations). The engineers Yu. V. Bobrov, V. V. Golubev, V. I. Protserov and the laboratory assistants Kardashev, V. N. Panov and K. I. Petrova participated in the creation of this receiver. The work was carried out under the supervision of Chikhachev, with astrophysical supervision from Shklovskii. In those years, there was very close collaboration between the radio astronomy departments of GAISH and FIAN, which no doubt facilitated success in the establishment of radio astronomy research in both institutions.

## 3.2 The First Ten Years of the Department of Radio Astronomy (1954–1964)

The beginning of the first decade of work in the Department of Radio Astronomy was marked by big scientific events. On March 9–12, 1955, the fifth meeting on questions of cosmogony, dedicated entirely to problems in radio astronomy, took place in the conference hall of the Sternberg Astronomical Institute. In essence, this was the first nationwide meeting on radio astronomy.

In the following years, the Department of Radio Astronomy filled up with new members. V. G. Kurt joined the department in 1955, and V. I. Moroz in 1956, followed somewhat later by G. B. Sholomitskii, T. A. Lozinskaya, G. S. Khromov, V. N. Kuril’chik, M. I. Pashchenko and others. This was the first generation of researchers in the department, most of whom were students of Shklovskii.

Solomon Borisovich Pikel’ner (Fig. 3.1) was invited to the Astrophysics Faculty of Moscow State University as a professor in 1959. He had graduated from the Astronomical Section of Moscow State University in 1942, and his first teacher

**Fig. 3.1** Solomon Borisovich Pikel'ner (1921–1975)

in his student years was none other than Shklovskii. After finishing his PhD and defending his thesis, Pikel'ner worked for more than ten years at the Crimean Astrophysical Observatory, in close collaboration with the important Soviet astronomy G. A. Shain. Having deeply imbibed of the tradition of his school, Pikel'ner himself became an eminent astrophysicist of our time. A person of unusual talent and rare personal qualities, he exerted a huge influence on a whole generation of Soviet astronomers. The many-sided scientific activity of Pikel'ner included close contact with GAISH Department of Radio Astronomy.

Pikel'ner was a theoretician with a very broad profile. He was one of the first to understand the importance of magnetic hydrodynamics for astrophysics. The main directions of his scientific work—cosmic electrodynamics, cosmic gas dynamics, plasma astrophysics—inevitably overlapped with problems in radio astronomy. Pikel'ner is associated with a number of important studies directly in the field of radio astronomy.

A large place in Pikel'ner's studies was occupied by the physics of gaseous nebulae, including supernova remnants. In 1956, he pointed out that the life times of the relativistic electrons in the Crab Nebula are appreciably shorter than the life time of the nebula itself, and proposed the presence of continuous electron acceleration in the Crab. The joint work by Pikel'ner, Ginzburg and Shklovskii in which they proposed a method for estimating the magnetic field in the Crab Nebula based on the location of the break in the nebula's radio spectrum dates to this same period. This method was further widely applied, and continues to be applied, in radio astronomy to estimate the ages and magnetic fields of various objects.

At the beginning of the 1960s, the idea that the interstellar gas was heated and ionised by ultraviolet radiation from stars was predominant. However, the observations of Faraday rotation of the plane of polarisation of cosmic radio sources that were known by that time did not agree with this picture. There were also difficulties in explaining the temperatures of neutral-hydrogen clouds implied by observations in the 21-cm line. Pikel'ner's analysis of these data showed that the interstellar medium was heated, not by ultraviolet radiation, but by soft cosmic rays.

Important theoretical studies were also carried out by Shklovskii in this period. In 1955, he showed that the optical emission of the jet emerging from the nucleus of the galaxy M87 is emission by relativistic electrons, and proposed a mechanism for the generation of these electrons. Although this particular work is concerned with optical emission, it was also of importance for radio astronomy, since it suggested that the idea that there was a single radiation mechanism acting in the radio and in the optical was applicable not only to Galactic, but also to extragalactic objects.

In 1953–1956, Shklovskii used synchrotron theory to estimate the energy ($10^{51}$–$10^{53}$ J) of the relativistic particles (and magnetic fields) in radio galaxies. Somewhat later, similar calculations were carried out by G. Burbidge, who obtained the same results. This sharply posed the question of the source of the energy of radio galaxies.

Shklovskii's book "Cosmic Radio Emission" (Moscow, USSR Academy of Sciences) came out in 1956. This was the first monograph on radio astronomy in the Soviet Union, and one of the first in the world. A whole generation of Soviet radio astronomers were trained on it.

In 1960, Shklovskii predicted the secular variation in the radio flux from the source Cassiopeia A, based on the picture of this object as an expanding supernova remnant. Building on this idea, he constructed a diagram relating the radio brightness of a supernova remnant with its distance, which provided a new (radio astronomy) method for determining the distances to supernova remnants, which has been put to good use in studies of these objects. In that same year, Shklovskii developed a theory of old supernova remnants by applying a self-similar solution for a strong explosion in a medium with a constant heat-capacity. Based on this theory, he predicted the existence of soft X-ray emission from supernova remnants.

The discovery of quasars in 1963 stimulated a number of studies by Shklovskii dedicated to these important astrophysical objects. Already in 1963, he hypothesised the variability of the optical emission of quasars. Based on this suggestion, GAISH researchers Yu. N. Efremov and A. S. Sharov analysed old photographs of the quasar 3C273 and, indeed, found that its emission was variable. Further, in a series of studies in 1963–1964, Shklovskii showed that the chemical composition of quasars coincides with the normal (in other words, solar) composition. In 1965, he predicted that the radio emission of active galactic nuclei and quasars should also be variable, and developed theory associated with this, which was subsequently fully confirmed by observations.

N. S. Kardashev was very active beginning in the second half of the 1950s. His most important theoretical work in these years was a calculation demonstrating the possibility of observing radio recombination lines arising in transitions between highly excited states of the hydrogen atom. He reported on these results at the Xth Assembly of the International Astronomical Union, which took place in the Summer of 1958 in Moscow. A search for new radio lines began both in the USSR and at major radio telescopes of the USA. These lines were first detected by two groups of Soviet radio astronomers, in Pulkovo and FIAN (see Essay 1). There is no doubt that this was one of the greatest achievements of Soviet radio astronomy. It is especially gratifying to note that all stages of these studies (from posing the problem, to establishing its theoretical basis, to observationally detecting the lines) were carried out in the Soviet Union. The authors of this discovery (E. V. Borodzich, Z. V. Dravskikh, A. F. Dravskikh, N. S. Kardashev and R. L. Sorochenko) were awarded a diploma dated August 31, 1964 for this work.

Toward the end of the 1950s, the manufacture of a correlation radiometer operating at a wavelength of 21 cm was completed in the Department of Radio Astronomy. In 1960, a group of researchers under the supervision of Kardashev began observations with this radiometer on the RT-22 radio telescope in Pushchino. The 21-cm continuum radio fluxes of a large number of diffuse gaseous nebulae were measured. In addition, Kardashev estimated an upper limit for the 21-cm line radiation, in other words, for the content of neutral hydrogen, in clusters of galaxies in Corona Borealis and Gemini.

Together with the observations in Pushchino, the distribution of neutral hydrogen in our Galaxy was studied using the radio telescope of the Crimean Station of FIAN. This work was carried out in close collaboration with FIAN scientists (Sorochenko, Chikhachev). Kardashev, O. N. Generalov, Lozinskaya, Kuril'chik and Lekht took part in these observations, and the observational data were reduced by N. F. Sleptsova and Lozinskaya. The results were used to construct a relief map of the distribution of hydrogen in the Galaxy, characterising the thickness of its hydrogen layers. The magnitude of deviations of the gaseous disk from the Galactic plane for various distances from the Galactic centre, characterising the deforming (bending) of the gaseous disk relative to the Galactic plane, were also obtained (Kardashev, Lozinskaya). This effect had been detected earlier by Australian and Dutch researchers. The Crimean observations made it possible to appreciably refine the available data for the Northern hemisphere, and also to extend them to much larger distances from the Galactic centre.

In 1962, Kardashev studied in detail the nature of the spectra of sources of nonthermal radio emission taking into account various mechanisms for energy losses and gains. Based on theoretical calculations, he derived information about the character of such spectra (their shape, cutoffs and breaks) and the expected behaviour for their time variations. This work was very important for our understanding of the processes occurring in non-stationary sources. In that same year, a group of authors from GAISH and FIAN (Kardashev, Kuz'min, Syrovatskii) published an article generalising the results of observations of Cygnus A in the Astronomicheskii Zhurnal. They determined the break frequency in the radio spectrum of Cygnus A and derived the first estimate of the age of this radio source—about 0.5 million years.

In 1962, observations on the large antennas of the Deep-Space Communications Centre at 32 and 7 cm were begun. Sholomitskii investigated radio sources in clusters of galaxies. In 1964–1965, he discovered variability of the radio source CTA-102. Kuril'chik carried out detailed studies of the radio emission of normal galaxies, while Khromov was interested in the radio emission of planetary nebulae. The observations of the occultation of the quasar 3C273 by the Moon had extreme importance, since they made it possible to identify the presence of a very compact component. At various times, M. G. Larionov, Sleptsova and others took part in this work. Many GAISH radio astronomers acquired very good training in radio astron-

**Fig. 3.2** G. B. Sholomitskii, I. S. Shklovskii and N. S. Kardashev (*left to right*) in the GAISH conference hall after the press conference about the radio emission of the source CTA-102 in 1965

omy observations in the Crimea, through the use of such modern and new equipment for that time as masers, parametric amplifiers and so forth.

Historically, the detection of variability of the radio emission of CTA-102 by Sholomitskii is of special interest. This source was selected because, based on its spectrum, Sholomitskii had suggested the possibility of secular variations of its radio flux, analogous to the variations of Cassiopeia A. At the same time, Kardashev, based on the hypothesis that this radio emission had an artificial origin, suggested the possibility that there might be periodic variations of the radio flux. The observations carried out by Sholomitskii in 1964–1965 confirmed the presence of periodic variations with a period of 102 days (Fig. 3.2). From an experimental point of view, this work was conducted with all due care: the flux of CTA 102 was measured (relative to the flux of the radio source 3C48), using as a control the source CTA 21 (which has a similar flux and is nearby on the celestial sphere), which did not show any radio-flux variations. All possible sources of error were investigated in detail and taken into account. Nevertheless, this result was met with a certain scepticism, in part due to the fact that it was completely unexpected and partly because the nature of the source had become associated with the hypothesis of extraterrestrial civilisations. The verification of the result by a number of observatories led to the discovery of a completely new and fundamental property of quasars—variability of their radio emission. However, the variability of the radio flux of CTA-102 was not confirmed. This effect was detected again only in 1972, by the Australian radio astronomer J. Hunstead, and then also by others. It is currently thought that the variability of this source has a transient nature, with intervals of variability and stability alternating in time.

In 1962, Sholomitskii considered the ratios of the radio fluxes of the lobes of double radio sources, as a possible consequence of Doppler effects acting during the expansion of these components. This idea was further developed by radio astronomers at Cambridge. In 1965, Kuril'chik pointed out the presence of strong evolutionary effects (variation of the radio luminosities of components with time), which he believed could play a dominant role in explaining the observed flux ratios.

Among other results obtained in the early 1960s, we should note the studies of synchrotron reabsorption by V. I. Slysh, which led to Slysh's well known formula for the estimation of the limiting angular sizes of sources of synchrotron radiation.

At the end of the 1950s, GAISH Radio Astronomy Department was actively involved in the programme of space investigations carried out in the Soviet Union. For example, Shklovskii established contact with S. P. Korolev and participated in the planning of many experiments. Kardashev and Slysh worked on the development of the first space radio telescope for observations of long-wavelength radiation (at frequencies below the critical frequency of the ionosphere).

The first successful measurements of long-wavelength radio emission at wavelengths of 150 and 1500 m using instruments created at the Sternberg Astronomical Institute were conducted on board the *Zond-2* and *Venera-2* spacecraft in 1964–1965.

## 3.3 The Search for Signals from Extraterrestrial Civilisations, and the RT-MGU and RATAN-600 Projects

To an appreciable extent, the development of radio astronomy at the Sternberg Astronomical Institute was held up by not having its own observational base. In spite of its large contribution to the development of radio astronomy, GAISH did not have its own radio telescope, and GAISH researchers were forced to carry out their observations using antennas that belonged to other institutions. This problem was partially addressed when GAISH participated in the equipping of the RATAN-600 radio telescope, which gave the right to continuous access to this instrument and the organisation of their own observational base there. The path that led to this solution was not trivial, and its beginnings were associated with a problem that falls outside the sphere of radio astronomy itself—the search for signals from extraterrestrial civilisations.

Interest in this problem grew at the end of the 1950s, at the dawn of space studies. Shklovskii and his colleagues began to discuss this question in the summer of 1961. The now widely known book of Shklovskii "The Universe, Life and Intelligence" (Moscow, USSR Academy of Sciences) came out in 1962, and subsequently had a large influence on the development of investigations of the question of extraterrestrial civilisations in the Soviet Union. Kardashev analysed the sending of information by extraterrestrial civilisations in detail. His main conclusion was that the level of technology used in ground-based radio astronomy should enable the detection of signals from highly advanced civilisations, provided only that they were located in our Galaxy, or even in neighbouring galaxies. This opened good perspectives for wide searches for such signals. In 1963, an initiative group was formed at GAISH (Kardashev, L. M. Gindilis, Slysh), which set the goal of drawing the attention of the scientific community to the problem of searching for signals from extraterrestrial civilisations and organising practical investigations with this aim. The overwhelming majority of scientists with whom this question was discussed considered the task to be quite reasonable. At the end of 1963, Shklovskii and Kardashev met with Ambartsumian, who suggested conducting a scientific meeting to provide a forum for multi-faceted discussions and estimating the state of this problem. This meeting took place in May 1964 at the Byurakan Astrophysical Observatory, and marked the beginning of studies of the search for extraterrestrial signals in the Soviet Union. The initiators of these studies were radio astronomers of Moscow State University.

The Byurakan meeting about studies connected with the detection of extraterrestrial signals included detailed analyses of radio sources in the centimetre and decimetre wavelength ranges that were most favourable for interstellar communications, with the aim of revealing possible artificial sources (according to the expected criteria for a signal being artificial). Kardashev put forward the idea of carrying out complete radio surveys of the sky at centimetre wavelengths. Naturally, this task was of considerable interest for purely radio astronomy purposes as well. Kardashev proposed the construction of a specialised meridian radio telescope operating at centimetre and millimetre wavelengths for this purpose. A Kraus-type radio telescope was adopted as the basis for this instrument. The development of a preliminary model of the radio telescope, which acquired the name "RT-MGU," was produced in 1964 in the Department of Radio Astronomy of GAISH. Kardashev, Slysh and Gindilis (who had transferred to the Radio Astronomy Department of the High-Mountain Station of GAISH) took part in this work. Substantial help in the development of the project was provided by P. D. Kalachev of FIAN.

The radio telescope was designed to operate at 0.4–10 cm. An antenna consisting of two reflecting surfaces—one parabolic and one planar—and a secondary mirror (feed) was envisioned. The horizontal reflecting suface was 414 × 8.2 m in size, and could rotate within 52° of the vertical, enabling coverage of a declination interval of 105° and making it possible to observe 80% of the entire sky at a latitude of 45°. The projected geometrical area of the antenna aperture was 2000 m$^2$, and the beam full-width at half-maximum size was $2.6'' \times 3.5'$ at 0.4 cm. The time for surveying the observable part of the sky was supposed to be 14.5 years at 0.4 cm and 0.5 years at 10 cm. The calculated minimum detectable fluxes at these wavelengths (for a bandwidth of 1000 MHz and a noise temperature of 100 K) were 0.25 and 0.05 Jy, respectively. The expected number of detected sources was of the order of several tens of thousands. In addition to carrying out the surveys, the telescope could be used to obtain high-accuracy measurements of the right ascensions and detailed one-dimensional maps of the source brightnesses. It was intended that the radio telescope could be outfitted by the end of the 1960s, and it would have had very good parameters for that time.

The cost of the planned RT-MGU radio telescope was two million rubles.[1] Unfortunately, the university was not able to allocate such a sum. The rector of

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[1] This sum is sometimes mistakenly taken to be the first stated price of the RATAN-600 telescope.

Moscow State University, Academician I. G. Petrovskii, who had always been sympathetic with the needs of radio astronomers, discussed with Keldysh, the President of the USSR Academy of Sciences, the possibility of outfitting the radio telescope jointly with the Academy of Sciences on a share basis. This proposal was approved, and the matter was given over to the USSR Academy of Sciences Scientific Council on Radio Astronomy. Simultaneously, the Radio Astronomy Section of the Main Astronomical Observatory proposed to outfit a radio telescope based on a variable-shape antenna constructed earlier for the same wavelength range and having a similar effective area for its operational section. During the discussion of both projects, it was decided to combine the two. The main reflecting surface of the variable-shape antenna was supplemented with a flat reflector making it possible to survey the sky with a knife beam (see Essay 5). This is how the RATAN-600 radio telescope project came into being. Moscow State University's share in the project was determined to be 300,000 rubles. The funding provided by the university made it possible to initiate the financing of the project and carry out initial work on the telescope. (For more detail about the creation of the RATAN-600 radio telescope see Essays 5 and 6.) Shkovskii, Kardashev, Gindilis and Zabolotnii from GAISH took part in developing the project. Further, A. E. Andrievskii participated in the planning of the radio-receiver complex. In addition, the Assistant Director of the Sternberg Astronomical Institute, P. S. Soluyanov, was closely involved in all matters having to do with the outfitting of the RATAN-600 radio telescope. In order to facilitate the successful fulfilment of this work, the Division of General Physics and Astronomy of the USSR Academy of Sciences appointed Gindilis as the authorised representative of the Division in connection with the RATAN-600 project. Simultaneously, Andrievskii was established as an assistant head construction engineer in connection with the receiver apparatus.

Immediately after the decision was made to construct the radio telescope (1966), the RATAN-600 group under the supervision of Gindilis was formed at GAISH. It was supposed that work associated with the RATAN-600 would occupy a very important place in the activity of the GAISH Department of Radio Astronomy. However, the beginning of the establishment of the Department of Astrophysics of the Space Research Institute of the Academy of Sciences in 1967 (based on the GAISH Department of Radio Astronomy) substantially changed these plans. This left primarily the youngest members of the Department of Radio Astronomy in the RATAN-600 group: A. E. Andrievskii, A. G. Gorshkov, M. G. Larionov, V. K. Konnikova and V. V. Danilov.

The theme of scientific studies of the Sternberg Astronomical Institute using the RATAN-600 telescope was set from the very beginning—conducting complete surveys at centimetre wavelengths. The group was given the task of creating a receiver complex suitable for survey work. By the time the first stage of the construction of the RATAN-600 began (1974), the main stages of this work had been completed. In 1974, a GAISH laboratory was established at the RATAN-600 site, whose acting head was Gindilis, with Larionov replacing him in this capacity in 1976.

## 3.4 Establishment of the Department of Astrophysics at IKI. Radio Astronomy at GAISH in the Transitional Period (Second Half of the 1960s)

In 1966, Shkovskii was invited to organise and head the Department of Astrophysics in the newly established Space Research Institute (IKI) of the USSR Academy of Sciences. This opened broad possibilities, first and foremost in the development of space-related research, which was intensively carried out in the GAISH Department of Radio Astronomy at the end of the 1950s.

The administration of IKI supported the point of view of Shklovskii that space studies should be developed in close association with ground-based observations. During the creation of the radio astronomy departments at IKI, the need to retain close ties with the GAISH Department of Radio Astronomy was also recognised, which ensured good training of young specialists.

Radio astronomy studies at IKI were headed by Kardashev. A number of leading GAISH radio astronomers went to IKI together with him, such as Slysh (to organise work first in low-frequency radio astronomy, then radiospectroscopy) and Sholomitskii (to develop work in submillimetre astronomy), as well as some GAISH engineers. L. I. Matveenko was invited from FIAN, and headed the radio interferometry section. A number of graduates of the Astronomy Department of Moscow State University also came to IKI in those years (I. E. Valtts, V. A. Soglasnov, V. A. Soglasnova, V. M. Charugin), as well as M. V. Popov, who had obtained his PhD at GAISH. V. S. Etkin and I. A. Strukov, who had extensive experience in the development of high-sensitivity amplifiers and had earlier established close contact with the GAISH Department of Radio Astronomy, were invited in the same period, to develop radio astronomy equipment in the IKI Department of Astrophysics. As the formation of radio astronomy departments at IKI proceeded, scientific work was conducted in collaboration with the GAISH Department of Radio Astronomy.

By the end of the 1960s, the preparation of the first version of a radiometer operating at 3.5 cm was completed in the RATAN-600 group under the supervision of Andrievskii, jointly with the Laboratory of Problems in Radio Physics, whose researchers V. M. Mirovskii, E. E. Spangenberg and V. V. Nikitin took part (under the supervision of Etkin and Strukov). In 1968, this radiometer was installed on the RT-22 radio telescope of the Crimean Astrophysical Observatory, and a large series of measurements of the 8550-MHz fluxes of radio sources was carried out. A large group of researchers from GAISH, IKI, the Laboratory of Problems in Radio Physics and the Crimean Astrophysical Observatory participated in this work.

The preparation of an addition to the radiometer enabling transfer of the data to a computer was completed under the supervision of Larionov in 1969. In April–May 1969, this apparatus was used to carry out the first Soviet survey of a section of the sky at 3.5 cm on the Crimean RT-22 telescope. These observations were conducted with the aim of working out methods for future surveys on the RATAN-600, but, of course, they had other independent scientific value as well. Their analysis of these survey data (together with data from the Ohio State survey at 21 cm) led

Gorshkov and Popov to infer the existence of a new population of Galactic radio sources forming a spherical component of the Galaxy.

By the end of the 1960s, the manufacture of a spectral radiometer operating at 21 cm was also completed in the GAISH Department of Radio Astronomy, which was developed and constructed over many years under the supervision of Pashchenko. This put the question of carrying out observations with this instrument on the agenda. Shkovskii was able to get the director of the Observatoire de Paris–Meudon to agree to conduct joint studies using the large radio telescope at Nancay. This was a very fortunate arrangement, since the Nancay telescope was by far the most suitable for these investigations. Since observations of radio lines of OH were considered to be the most promising, the high-frequency part of the receiver was adjusted to enable observations at 18 cm. This collaboration with the Meudon Observatory was very fruitful. The equipment used was subsequently considerably modernised. The first observations at Nancay were carried out in 1969 (Slysh, Pashchenko, Lekht, Strukov). In the following years, from 1969 to 1978, researchers of GAISH and IKI conducted a series of very valuable studies of regions of OH emission using the Nancay telescope (see Essay 6). The spectral radio astronomy group of GAISH was formed during this work (Pashchenko, Lekht, Rudnitskii).

In that same period, work on equipment suitable for millimetre and submillimetre astronomy began at GAISH at the initiative of Kardashev. At first, this work was assigned to the Oimyakonskii Station of GAISH. Emission at submillimetre and far infrared wavelengths are absorbed by water vapour in the Earth's atmosphere. The most radical means to remove this limitation was to place an observing device outside the atmosphere. The absorption can be decreased by choosing a site on the Earth's surface where there is a low water-vapour content in the atmosphere. This condition is satisfied by high mountainous regions and regions with very low temperatures. A station was organised near the North Pole (the Oimyakon settlement, Irkutsk), to measure the atmospheric opacity in the infrared and submillimetre ranges and to evaluate possibilities for observations at these wavelengths. The apparatus used was constructed with the participation of the Moscow State Pedagogical Institute (E. M. Gershenzon, I. K. Morozov, Etkin). N. V. Vasil'chenko, Kardashev, Moroz, Morozov, Repin and Khromov took part in the work of this station. Observations were carried out in February 1966 at a temperature of $-60$°C. However, the water content of the atmosphere turned out not to be as low as had been expected (only an order of magnitude lower than at middle latitudes in the European part of the USSR in wintertime). This was due to the presence of a stable temperature inversion (in height). Analysis of these measurements indicated that regions in Eastern Siberia were promising for observations at 1 mm, but could not compete with balloon flights for measurements at wavelengths shorter than 300 μm.

Researchers at IKI continued to search for an optimal place for ground-based observations, leading to the selection of two locations: the mountains of southern Uzbekistan for millimetre observations, and in the high-mountain part of Pamira for submillimetre observations (see Sect. 3.5).

The development of techniques for measurements at millimetre and submillimetre wavelengths was worked on by Zabolotnii at GAISH and Sholomitskii at IKI.

A submillimetre radiometer based on an “electron bolometer” cooled by liquid helium to a temperature of 4.2 K was developed during 1967–1968. A series of observations at 1–2 mm wavelength were carried out with this radiometer installed on the Crimean Astrophysical Observatory RT-22 telescope in 1969–1975. Zabolotnii, Slysh, Soglasnova, Sholomitskii and others took part in these observations. In spite of the fact that the RT-22 surface was not designed for these wavelengths and the humidity was fairly high during the observations, a sensitivity of about 10 Jy was realised for an hour integration time. The brightness temperatures of all the giant planets of the solar system were measured at 1.4 mm, as well as the fluxes of a number of Galactic (the Crab Nebula, NGC 7027, W51, W49) and extragalactic (NGC 3034, 3C273 and others) sources.

In the second half of the 1960s, as in earlier years, intensive theoretical studies were conducted in the GAISH Department of Radio Astronomy. The year 1965 was marked by a number of important discoveries in radio astronomy. The most fundamental of these was the detection of the “relict radiation”—the cosmic microwave background radiation. The possibility of detecting this radiation was predicted by Novikov, who began this work at GAISH and is now working at the IKI Department of Astrophysics, and by A. G. Doroshkevich. In 1964, they calculated the entire spectrum of the radiation at all wavelengths from all sources in the Universe (radio galaxies, radio stars and so forth), taking into account their possible evolution, the expansion of the Universe and other cosmological effects. They showed that, if the Universe was indeed hot at the beginning of its expansion, the residual “relict radiation” at centimetre and millimetre wavelengths should be many orders of magnitude higher than the total radiation from discrete sources, and should be detectable. The cosmic microwave background radiation was discovered a year after by A. A. Penzias and R. W. Wilson (USA). The value of the work of Soviet scientists was noted in the Nobel lecture given by Penzias (see also Essay 4).

The term “relict radiation,” which has become well established in the language of modern science, was proposed by Shklovskii. Later, in 1966, he proposed a method for determining the temperature of this radiation based on the intensity of optical molecular lines emitted by the interstellar gas (CN and other molecules).

In 1965, Kardashev calculated a model for the generation of the magnetic field of the neutron star (essentially a pulsar!) in the Crab Nebula. It is interesting that this work was carried out three years before the discovery of pulsars, and, of course, the very term “pulsar” did not exist at that time. Kardashev showed that the neutron star that formed after the supernova explosion of 1054 should have a very strong magnetic field. As the star rotates on its axis (with a period of less than one second), the magnetic field lines in the envelope are “wound up” by the rapid rotation of the neutron star. This field is the magnetic field of the Crab Nebula. This work of Kardashev has great importance for our understanding of the physics of the Crab Nebula and similar objects. The theory of the emission of the Crab pulsar was developed by Shklovskii in 1970.

## 3.5 Radio Astronomy Research at IKI

Radio astronomy research was methodically developed in the following directions: (1) space radio telescopes and methods for radio astronomy studies in space; (2) very long baselines radio interferometry; (3) studies of the propagation of radio waves in the interstellar medium; (4) analysis of fine temporal structure of rapidly variable processes using synchronous observing methods; (5) spectral studies; (6) submillimetre studies; (7) studies of the nature of radio sources; (8) searches for radio signals from extraterrestrial civilisations; (9) theoretical research.

**Space Radio Telescopes and Methods for Radio Astronomy Studies in Space** Work on large radio telescopes has been conducted under the supervision of Kardashev beginning in 1967.

In 1968–1970, the possibility of realising an Earth–Moon interferometer was studied in the IKI Department of Astrophysics in collaboration with the Observatoire de Paris–Meudon. Kardashev, Slysh and Matveenko took part on the Soviet side, and Bloom, Denis, Leke and Steinberg on the French side. These studies (Matveenko et al.) showed that it was optimal to place the space radio telescope into an orbit around the Earth.

In 1970, Kardashev and Pariiskii demonstrated that space interferometers provide the unique possibility of obtaining three-dimensional images of radio sources and directly determining the distances to these sources. They also showed the possibility of obtaining direct measurements of the cosmological curvature of space and the main cosmological parameters, since the entire Universe would be located in the near field zone of an interferometer baseline with a length of several astronomical units (one AU is the distance from the Earth to the Sun). At the initiative of Ginzburg, the first broad discussion of the scientific and technical problems associated with space radio astronomy was conducted in December 1970.

The major specialists of the Institute of Project Construction A. G. Sokolov and A. S. Gvamichava, as well as V. I. Usyukin of the Bauman Moscow Higher Technical Institute, were recruited to develop methods for the construction of space radio telescopes. In subsequent years, new organisations and specialists in various scientific and technical fields who understood the importance and promise of constructing a radio telescope in space were attracted to this work.

In 1968–1978, many varied radio-telescope construction designs (with reflector sizes from 10 m to several kilometres) were analysed, together with methods for deploying the telescopes: inflatable elements, opening by centrifugal forces, the use of reactive motions, etc. In addition to options with some sort of automated deployment, constructions that could be deployed with the aid of cosmonauts were also considered. The direct supervision of all these studies was provided by Kardashev. A large amount of help in organising work on the construction of space radio telescopes was given by the President of the USSR Academy of Sciences Keldysh, and then A. P. Aleksandrov, as well as the Vice President of the USSR Academy of Sciences and Chairman of the Scientific Council on Radio Astronomy V. A. Kotel'nikov.

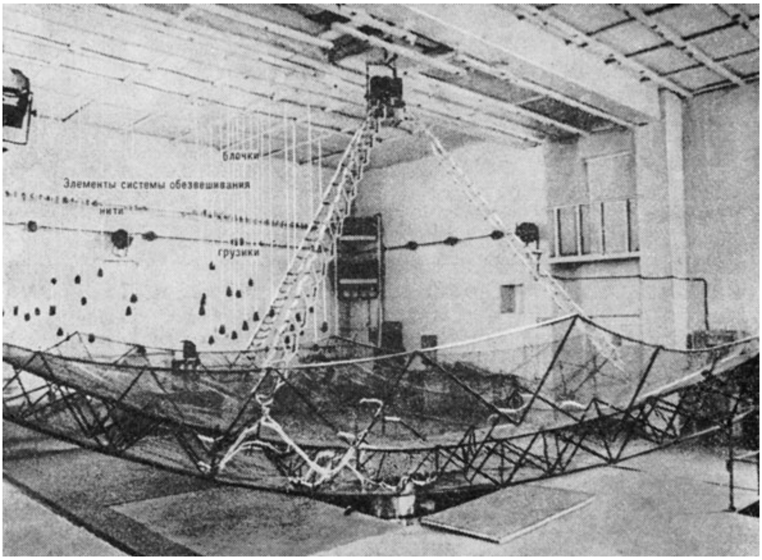

**Fig. 3.3** 10-m space radio telescope undergoing testing

These investigations met with success in 1979: the first space radio telescope—the KRT-10, with a diameter of 10 m—was constructed and put into orbit (Fig. 3.3). On June 30, 1979, the “Progress-7” cargo spaceship transported the KRT-10 components to the “Salyut-6” orbiting station. The cosmonauts V. A. Lyakhov and V. V. Ryumin assembled the antenna and focal container together with 12 and 72-cm receivers inside the adapter bay, and the low-frequency blocks and controlling device inside the instrument bay. On July 18, 1979, the “Progress-7” left the station, and the space radio telescope was moved out and deployed. During testing of the telescope, methods for radio astronomy observations in free space were developed for the first time. The Soviet scientists N. S. Kardashev, V. M. Arsent’ev, V. D. Blagov, A. S. Gvamichava, Yu. I. Danilov, v. I. Verzhatii, G. A. Dolgopolov, I. B Zakson, V. A. Krasnov, Yu. P. Kuleshov, I. M. Moshkunov and A. G Sokolov were awarded a State Prize for this work.

Substantial contributions to the construction of the space radio telescope were also made by V. I. Altunin, V. V. Andrianov, V. I. Buyakis, Sh. A. Vakhidov, L. A Gorshkov, V. V. Klimashin, V. I. Komarov, N. P. Mel’nikov, G. S. Narimanov, N. Ya. Nikolaev, M. V. Popov, V. A. Rudakov, A. I. Savin, R. Z. Sagdeev, Yu. P. Semenov, V. S. Troitskii, K. P. Feokistov, G. S. Tsarevskii, I. S. Shklovskii, V. S. Etkin and other Soviet scientists.

Possibilities for realising long-term operation of space radio telescopes were investigated at IKI in the 1970s. More distant prospects for space radio astronomy were also studied (the possibility of constructing large modular antenna structures and putting them into very high orbits, with sizes of one astronomical unit or more). This could open possibilities for posing problems associated with astrophysics and the search for extraterrestrial civilisations on a completely new level. In particular, as was shown by Kardashev, Pariiskii and Yu. N. Umarbaeva (Special Astrophysical Observatory, USSR Academy of Sciences) in 1973, three space radio telescopes in high orbits could comprise a new type of instrument that could be used to determine the three-dimensional structure of a cosmic radio source by measuring the curvature of the incident radiation (the method of radio holography).

**Very Long Baseline Radio Interferometry (VLBI)** The idea of creating very long baseline radio interferometers using independent (unconnected) antennas was proposed in the early 1960s by Matveenko, Kardashev and Sholomitskii, and was published in the journal *Radiofizika* in 1965. This idea was not realised in a practical sense at GAISH, and this work was carried out at FIAN by Matveenko.[2] In 1969, Shklovskii invited Matveenko to IKI for the purpose of organising radio interferometry studies in the newly created Department of Astrophysics. In that same year, it was decided to move work on VLBI from FIAN to IKI. Matveenko headed the Radio Interferometry Section organised at IKI. Together with theoretical investigations of possibilities for creating space interferometers (see above), experimental studies using ground-based telescopes were begun in the Radio Interferometry Section. During the first years, while the necessary experimental base was being established at IKI, work on radio interferometry conducted using the equipment of FIAN and the Crimean Astrophysical Observatory.

The first Soviet–American experiment between Simeiz and Green Bank was realised in 1969, and a new experiment involving Simeiz, Green Bank and Goldstone in 1970. Observations were carried out at 2.8, 3.6 and 6 cm. As a result of these observations, the possibility of obtaining very high resolution (several tenths of a milliarcsecond) at centimetre wavelengths on intercontinental baselines was shown for the first time. Further, through the joint efforts of a number of countries, a global interferometric array was created, which includes the RT-22 telescope of the Crimean Astrophysical Observatory. This array, which operates at wavelengths of 1.35 and 18 cm, could form the main ground-based array for a space radio interferometer. Experiments are carried out regularly with the participation of a number of organisations of the Soviet Union, USA, Sweden, the Federal Republic of Germany, Australia, England and Italy: at first two or three, and then four or five experiments per year.

The experiments conducted with the participation of IKI (Matveenko, L. R. Kogan, V. I. Kostenko and others) studied two types of objects: extragalactic objects with active nuclei (quasars, radio galaxies, BL Lac objects) and star-forming regions with $H_2O$ and OH maser sources. Data were obtained about the detailed structures of quasars, the structure of their magnetic fields and their brightness temperatures, which proved to be $10^{12}$ K or higher for individual components in the source structure. In some cases, apparent motions of components faster than the speed of light were observed.

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[2] At about the same time, work on the development of VLBI was begun at the Main Astronomical Observatory by N. L. Kaidanovskii (see Essay 4).

Simultaneous with this international program, IKI together with FIAN and the Crimean Astrophysical Observatory took part in establishing a Soviet interferometer operating between Simeiz and Pushchino. The specifications for this interferometer established by the Scientific Council on Radio Astronomy of the USSR Academy of Sciences and confirmed by the Division of Physics and Astronomy of the USSR Academy of Sciences foresaw the use of an interferometer comprised of the RT-22 radio telescopes of FIAN and the Crimean Astrophysical Observatory, together with a complex of computer-based equipment, hydrogen-maser frequency standards operating at 1.35 cm and other equipment. The construction of the interferometer was finished in the middle 1970s, and systematic observations of water-maser sources were begun in 1976. In 1982, the RT-70 telescope was added as another interferometer element. In addition, the new wavelength of 18 cm began to be used, which appreciably expanded the capabilities of the interferometer.

As a result of joint studies on this instrument and the global VLBI network at 1.35 cm, the structures of regions of star formation could be studied in detail. It was established that the sources of $H_2O$ emission were concentrated in individual centres of activity about 1000 astronomical units in size, with the sizes of the sources themselves being about one astronomical unit. The maser sources in an activity centre were located in disks or rings, with a protostar with a mass of 1–20 times the mass of the sun. One set of important results obtained using the Simeiz–Pushchino interferometer were derived from studies of $H_2O$ “flares” in the source Orion-4.

**Investigations of Rapidly Variable Processes Using Synchronous Observations** Studies aimed at detecting radio flares arising during supernova explosions were undertaken at IKI at the beginning of the 1970s. All-directional antennas and wideband receivers operating at several decimetre and metre wavelengths were used. The receiving antennas were separated by large distances (thousands of kilometres), making it possible to exclude a large fraction of the local interference (by analysing impulsive events synchronous at different antennas). Signals originating in space could be identified from the delay in their signals at low frequencies relative to high frequencies; the magnitude of this delay, which is determined by the dispersion measure in the interstellar medium, could then, in principle, be used to estimate the distance to the source. This method became known as synchronous dispersional signal reception. Together with searches for supernova flares, this method was used to carry out searches for signals from extraterrestrial civilisations. This work was conducted by Popov, Soglasnov, E. E. Spagenberg and V. Sysoev under the direction of Kardashev. Workers at the Moscow State Pedagogical University, Sternberg Astronomical Institute and Moscow Energy Institute took part in the development of the equipment and in the observations. In 1972, observations were carried out at two points: in the Northern Caucasus and Pamir. The Caucasus station continued to operate in 1973, and a new station was set up at Kamchatka, in order to increase the baseline between the antennas, and thereby more effectively exclude interference from Earth-orbiting satellites. In addition, a French setup operating at metre wavelengths was installed at these ground stations and on board the *Mars-7* spacecraft in the framework of a joint Soviet–French experiment. These observations led to the detection of several types of coincident impulses, due to radiation from the ionosphere (detected earlier by Gorkii radio astronomers), solar flares and interference from Earth-orbiting satellites. No cosmic signals with appreciable dispersions were detected. Synchronous searches of impulsive signals using widely separated omnidirectional antennas were ceased in the middle 1970s. The synchronous-dispersion method began to be used jointly with observations on directional antennas (the 22-m radio telescopes in the Simeiz and Pushchino and the 100-m radio telescope in Germany) in connection with investigations of individual peculiar sources.

In 1974, the first synchronous observations of pulsars aimed at measuring correlations of the fluctuations of the mean pulse intensities were carried out on the Simeiz and Pushchino 22-m telescopes. Unfortunately, it was not possible to obtain observations sufficient for the cross-correlation analysis due to the presence of interference in the Pushchino data. However, the Simeiz data yielded the mean profiles and scintillation curves for several pulsars (PSR 0329+54, PSR 0950+08, PSR 1133+16 and PSR 1929+10).

The experiment was repeated in 1977 with PSR 0329+54 at a frequency of 550 MHz (with a channel bandwidth 5 MHz), but the interference proved to be even worse. Therefore, it was not possible to obtain observations that were free from interference simultaneously at two different sites.

A more successful set of synchronous observations was conducted in 1977 and 1980 at Pushchino on the DKR-1000 telescope (102.5 MHz) and at Effelsberg (Federal Republic of Germany) on the 100-m telescope (1700 MHz), as part of a cooperative Soviet–West German programme with the participation of IKI and FIAN. The resulting data were used to determine the location of the radio-emitting region in PSR 1133+16. Correlations between the mean intensities of pulsar pulses at frequencies of 102.5–1700 MHz were also found, together with the frequency dependence of the drift parameters for PSR 0808+74. Finally, in 1979, an experiment was carried out synchronously between the 70-m radio telescope of the Deep-Space Communications Centre and the 10-m radio telescope on board the *Salyut-6* orbiting station.

During the processing of these two-antenna experiments at IKI, a data-registration complex based on an *Elektronika-100I* mini-computer and *IZOT* recorders was developed. This complex was also used for 102.5 MHz observations of pulsar pulses with high time resolution (to 10 microseconds) starting in 1976, conducted in collaboration with FIAN on the Large Scanning Antenna in Pushchino. A dispersion-compensation method was applied, making it possible to greatly reduce smearing of the pulses due to dispersion during the propagation of the radio waves in the interstellar medium. This method was used in observations of ten of the brightest pulsars, in order to derive the characteristics of the microstructure in their pulses.

The method of synchronous observations was also used in studies of the Galactic centre.

**Submillimetre Astronomy** This area began to be developed at IKI immediately after the formation of the Department of Astrophysics at the end of the 1960s, when observations on the 22-m Pushchino antenna were conducted jointly with GAISH (see above), and then continued in the Laboratory of Submillimetre Astronomy under Sholomitskii. An appreciable part of the laboratory's work was associated with the development of the main components of receiver nodes—band spectral filters, optico-mechanical modulators, etc. These components were tested in airplanes and on ground-based telescopes.

In 1979–1981, a series of observations of quasars was conducted on the 6-m optical telescope of the Special Astrophysical Observatory of the Academy of Sciences, in collaboration with the group of G. V. Schultz at the Max Planck Institute for Radio Astronomy in Bonn. Observations were obtained at 1 mm wavelength (270 GHz) with a sensitivity of 0.3–0.5 Jy for an acculation time of one hour. The fluxes of 20 quasars were measured with this sensitivity. Comparison with data obtained by other groups demonstrated that some of the quasars had their maximum flux at 1 mm.

Simultaneously, investigations into selecting a site for ground-based submillimetre observations were conducted. In 1980–1981, the water-vapour content and atmospheric opacity at Shorbulak (East Pamir), at an altitude of 4350 m, were analysed in collaboration with the Main Astronomical Observatory. These studies established that Shorbulak was a very high-quality site for ground-based submillimetre observations, which was not surpassed in terms of its atmospheric transparency even by the well known high-altitude observatory at Mauna Kea (Hawaii, USA, 4200 m altitude).

*Theoretical studies.* These were led at IKI by Shklovskii in the Department of Astrophysics. Although the scientific interests of Shklovskii made a substantial shift into the new and vigorously developing field of X-ray astronomy in the 1970s, he also continued to work intensively in radio astronomy. In 1974, he successfully applied the theory of a relativistically expanding synchrotron source developed by Rees to explain the jet in NGC 4486. Shklovskii treated this object like a succession of magnetised clouds of plasma—"plasmons"—ejected from the active nucleus of the galaxy at relativistic speeds. Because of relativistic Doppler beaming, the intensity of the radio emission of plasmons moving in the direction of an observer is sharply enhanced, while the emission in the opposite direction is suppressed, providing an explanation for the one-sided appearance of the jet. Shkovskii returned to the problem of one-sided jets in 1981, emphasising their importance for our understanding of the nature of quasars.

At the end of the 1970s and beginning of the 1980s, L. S. Marochnik (a student of S. B. Pikel'ner) and a group of theoreticians headed by I. D. Novikov joined the theoretical group in the IKI Department of Astrophysics. The main area of interest of this group was cosmology and relativistic astrophysics. However, a number of their studies had a direct connection to radio astronomy.

As early as 1968, Novikov showed that, if the Universe is uniform, the onset of the cosmological expansion was anisotropic and the density $\rho$ was less than the critical density $\rho_{cr}$, the "relict radiation" should display a characteristic distribution on the sky: the intensity of this radiation should be nearly constant over the entire sky, except for a spot of enhanced (or reduced) intensity with an angular size of the order of $\Omega = \rho/\rho_{cr}$. These results were generalised to the case of arbitrary deviations from isotropy and spatially very large perturbations of the homogeneity of the Universe in studies by Doroshkevich, V. N. Lukash and Novikov.

Doroshkevich, Novikov and A. G. Polnarov examined the influence of cosmological gravitational waves on the observed anisotropy of the cosmic background radiation in 1977. In 1980, M. M. Basko and Polnarev carried out an exact calculation of the effect of the polarisation of the cosmic background radiation in the case of anisotropy in the expanding Universe. An important result of these calculations is that the degree of polarisation is very sensitive to heating of the intergalactic medium during the formation and evolution of galaxies.

**Radio Astronomy and Cosmology. Radio Astronomy Studies in the IKI Department of Theoretical Astrophysics** Starting in the middle of the 1960s, the extremely strong theoretical physicist Ya. B. Zel'dovich actively began a series of studies in astrophysics. Over a short time, he assembled a group of talented young scientists, many of whom came to his group directly from university. At first, Zel'dovich's group worked in the Institute of Applied Mathematics of the Academy of Sciences, also having close connections with GAISH, where the unified astrophysical seminars took place and where Zel'dovich gave a course for students in the Astronomy Department of Moscow State University. Early in 1974, part of the group was moved to IKI, where the Department of Theoretical Astrophysics was formed under the supervision of Zel'dovich. The main areas of interest of this department were associated with cosmology and relativistic astrophysics. Here, we will touch upon only those studies that had a direct connection to radio astronomy.

These were, first and foremost, related to the relict radiation. In 1966, immediately after the discovery of the cosmic background radiation, Zel'dovich gave an interpretation based on a hot Universe, and began to develop the theory of this hot Universe. A large series of works by Zel'dovich and his students were subsequently dedicated to this topic. In 1970, Zel'dovich and Sunyaev showed that, as a consequence of energy released in the early stages of the evolution of the Universe, the spectrum of the cosmic background radiation should differ from that for a blackbody. In a series of studies (1969, 1970), they analysed the variations of the spectrum expected for various energy losses. These effects were then studied in more detail by I. F. Illarionov and Sunyaev (1974). It was shown that there should exist two main types of spectral distortions arising in early stages of the evolution of the Universe. Thus, detailed analyses of the spectrum of the cosmic background radiation can yield the epochs for specific types of energy loss (effectively dating these losses).

A completely different type of distortion of the cosmic-background spectrum is due to recombination of hydrogen in the Universe at a redshift of $z \approx 1500$. As was demonstrated by Zel'dovich, Kurt and Sunyaev in 1968, radiation associated with two-photon transitions and Lyman-$\alpha$ emission lead to the appearance of bands in the submillimitre part of the spectrum. Calculations of the recombination for a non-equilibrium cosmic-background spectrum carried out in 1983 by Yu. E. Lyubarskii and Sunyaev showed that the recombination lines of hydrogen and helium were accessible to observations using radio telescopes with the sensitivity available at that time.

A number of papers by Zel'dovich and Sunyaev were dedicated to studies of fluctuations of the cosmic background radiation. In 1970, they calculated the fluctuations arising at the epoch of recombination, $z \approx 1500$, due to scattering of the background radiation on electrons moving in a field with only small density inhomogeneities, whose subsequent growth led to the formation of galaxies and clusters of galaxies. Thus, it was shown that studies of the fluctuations of the cosmic background radiation could provide very valuable information about the formation of galaxies and galaxy clusters.

The observed background fluctuations are due to both genuine fluctuations in the cosmic background radiation and fluctuations in the distribution of radio sources. Their contribution was studied by M. S. Longair (England) and Sunyaev in 1968. More detailed investigations of the fluctuations $\Delta T/T$ on various angular scales $\theta$ were carried out by P. B. Partridge (USA) and Sunyaev in 1982, whose calculations indicated a minimum in the function $\Delta T/T(\theta)$ on an angular scale of $\theta \sim 10'$. This determines the most promising scale for searches for intrinsic fluctuations.

The next series of works was associated with counts of radio sources. Observations show that the growth in the number of sources with increasing redshift $z$ ceases at $z = 2$. This led to the idea that all radio sources were born at $z < 2$. In 1968, Doroshkevich, Longair and Zel'dovich established that another completely different interpretation was possible: radio sources were born at $z > 2$, but live a finite time, over which there was a "decay", or sharp decrease in the number of sources (analogous to radioactive decay) according to an exponential law. This model to explain the "evolutionary effect" is currently widely accepted.

An important research direction was associated with studies of clusters of galaxies. In 1973, Zel'dovich and Sunyaev determined that, during the formation of clusters, in the evolution of so-called pancakes (protoclusters of galaxies), there is a stage ($z \sim 3$–$10$) when their central regions are in the form of gigantic ($M \approx 10^{13}$–$10^{14}$ solar masses) clouds of neutral hydrogen at a temperature of $T \sim 10^4$ K. Such clouds could be observed via their 21-cm lines, shifted toward the red to metre wavelengths.

In 1972–1982, Zel'dovich and Sunyaev carried out a series of investigations into interactions of the cosmic background radiation and the intergalactic gas in clusters of galaxies. They showed that, when background photons are scattered on electrons in the hot intergalactic gas, they are shifted toward higher frequencies, making clusters powerful sources of submillimetre and short-millimetre wavelength radiation. The opposite effect is observed at centimetre and longer millimetre ($\lambda > 2$ mm) wavelengths: the cluster becomes a negative (!) source; in other words, scanning of the sky should reveal a reduction in the brightness of the cosmic background radiation in the direction toward a cluster. This so-called Sunyaev–Zel'dovich effect was observed in a number of galaxy clusters by Y. N. Pariiskii in 1972, as well as by English, American and West German radio astronomers. Combined with the information from X-ray observations, measurements of this effect can be used to determine the linear size of the cluster, and therefore its distance and the Hubble constant. Another important conclusion that flows from the existence of the Sunyaev–Zel'dovich effect is that it provides experimental proof that the cosmic background radiation was created in early stages of the evolution of the Universe.

Zel'dovich and Sunyaev obtained a fundamentally important result in 1980: they showed that all clusters of galaxies could be "tied" to an absolute coordinate system defined by the condition that the cosmic background radiation is isotropic in this system. Consequently, the cosmic background radiation is playing the role of a new "ether". If a galaxy cluster with gas moves relative to this coordinate system with a speed $v$, the brightness of the cosmic background radiation in the direction of the cluster will vary in proportion to $v/c$, and a polarised component of the radiation will appear. Measurements of the brightness and polarisation of the cosmic background radiation in the cluster direction can be used to derive the velocity of motion of the cluster relative to the background radiation.

Other research that forms part of the series of studies concerned with clusters of galaxies is Sunyaev's work on their diffuse radio emission. He showed that, if there is a bright source in the cluster, scattering of its radiation on the intergalactic gas leads to a diffuse radiation component in the cluster, characterised by an extremely high degree of polarisation, $\sim$33–66%. This effect was calculated for the Virgo and Per A clusters, and observed with the RATAN-600 telescope and the 100-m Effelsberg radio telescope. Since the diffuse radiation is delayed relative to the direct radiation from the source, it provides information about the brightness of the source at earlier epochs (up to a million years earlier than the epoch of the direct radiation from the source).

Another series of studies by Sunyaev was concerned with observations of radio lines. In 1966, he noted the importance of observations of hyperfine splitting of the $\lambda = 3.46$ cm line of the $\mathrm{He}^{3+}$ ion, and calculated the parameters of this line, which was detected in observations made with the 100-m Effelsberg telescope. In 1968, L. A. Vainstein and Sunyaev performed calculations of two-electron recombination, and showed that it can lead to extremely strong population of the upper levels of a number of ions. Lines arising due to transitions between these levels should be observed in the spectra of quasars and of the Sun at centimetre to millimetre wavelengths, however, these lines have not been detected thus far.

In 1969, Sunyaev pointed out that observations of the periphery of a galaxy in the 21-cm line could provide unique information about the spectrum and intensity of the background ionising radiation of the Universe ($\lambda < 912$ Å). The ionisation of hydrogen at the edge of the galaxy by this radiation should be reflected in the 21-cm isophotes. Since this radiation is absorbed by neutral hydrogen at the periphery of our own Galaxy and therefore does not reach the solar system, this provides the only possibility of using 21-cm radio observations to estimate the intensity of the background ionising radiation.

The 1972 work of V. S. Strel'nitskii and Sunyaev on the acceleration of $H_2O$ maser sources near hot O stars is of considerable interest. The acceleration is brought about by the radiation of the hot stars and by shocks. This can explain the high velocities (up to 200 km/s) with which $H_2O$ maser sources leave the star-formation regions with which they are associated for the interstellar medium (the "Flying Dutchman" effect).

The works of Zel'dovich and his students laid new pathways in radio astronomy, closely associated with cosmology. This research transformed radio astronomy from a science concerned with various individual processes in the Universe, into a science providing valuable information about the evolution of the Universe as a whole.

## 3.6 Radio Astronomy at GAISH in the Post-transition Period

Radio astronomy research at GAISH developed in the following directions during the 1970s: surveys of the sky on the RATAN-600 telescope, spectral studies, studies of kilometre-wavelength cosmic radio emission using instruments on board spacecraft, submillimetre astronomy and theoretical studies.

**Sky Surveys on the RATAN-600** In accordance with the ideas behind its design and realised by its construction, this radio telescope is excellently suited for all-sky surveys. The knife antenna beam makes it possible to carry out comparatively rapid surveys of an appreciable area of the celestial sphere at centimetre wavelengths with high angular resolution in one coordinate. Another important feature is the ability to conduct observations simultaneously at several frequencies. This makes it possible to obtain instantaneous radio spectra during a survey. In contrast to earlier surveys, a multi-frequency survey on the RATAN-600 at 2, 3.5, 7.6 and 18 cm is being planned. Several receiver complexes operating at these wavelengths are being constructed in the RATAN-600 laboratory (partially on its own, partially in collaboration with other organisations). This work was done under the supervision of V. R. Amirkhanyan. The main wavelength of the survey is 7.6 cm.

Large databases require fully automated observation and data-processing procedures. With this idea in mind, a digital and computational complex was developed at GAISH under the supervision of M. G. Larionov. The main principles behind the mathematical reduction algorithms were due to A. G. Gorshkov, and work on the mathematical side of the complex was carried out under his supervision.

The survey observations were begun in 1978. The survey was carried out on the Southern sector of the RATAN-600 using two radiometers at 2 and 3.5 cm. A radiometer operating at 7.6 cm was added in 1979.

A survey of a section of the sky at declinations 0–7.5° was conducted in 1981, with the participation of Amirkhanyan, Gorshkov, A. A. Kapustkin, V. K. Konnikova, A. N. Lazutkin, Larionov, A. S. Nikanorov, V. N. Sidorenkov, L. S. Ugol’kova and O. N. Khromov. Of 650 sources detected in a 0.17-steradian area of the sky, 370 proved to be new objects that had never been mapped before; in other words, the number of new sources detected in the survey exceeded the number of previously known sources. This fully confirmed preliminary estimates made by Kardashev in 1964, who argued for the importance of carrying out surveys at centimetre wavelengths. This was the first survey in the Soviet Union that yielded a large number of new radio sources (apart from the Khar’kov survey, conducted at decametre wavelengths).

Analysis of the instantaneous spectra of the radio sources found in this survey showed that the mean spectral index at 2–3.5 cm was $0.4 \pm 0.4$, roughly the same as had been obtained for non-instantaneous spectra at centimetre wavelengths. This was a very important result, since it indicated that the spectral characteristics of variable radio sources could be studied using non-simultaneous observations at different wavelengths.

The distribution of the 7.6-cm survey sources was found to be uniform on the sky. The survey data provided information about the angular (and linear) sizes of an appreciable number of quasars and galactic nuclei, and confirmed the dependence of the number of observed sources on their radio flux derived earlier using survey data at other frequencies, which indicates the presence of substantial evolutionary effects.

**Spectral Observations** Productive studies of OH radio lines were carried out at GAISH in the 1970s using the Nancay radio telescope (Lekht, Pashchenko, Rudnitskii). Observations at 18 cm required a number of modernisations of the telescope, and a new receiver system was developed by staff of GAISH in collaboration with colleagues at the Meudon Observatory.

Interest in OH maser sources was stimulated by the role they played in star formation (the idea that there was a connection between maser sources and the early stages of star formation was first put forth by Shklovskii). In 1972, Pashchenko and Slysh discovered dense molecular clouds 3–5 pc in size with densities of $10^3$ cm$^{-3}$ near type I OH maser sources, via their absorption in the OH lines. A physical relationship was established between these clouds, the sources of type I OH masers and compact HII regions. Several years later, these same researchers found regions of extended maser emission in satellite lines near compact type I OH masers that were radiating intensely in the main OH lines. It was shown that this extended maser emission comes from the dense molecular clouds discovered earlier. This opened the possibility of obtaining information about the structure and physical parameters of the molecular clouds from observations in the satellite OH lines (together with observations of their absorption in the main lines). This essentially represented a new method for studying the interstellar medium, which is especially effective in (the many) cases when there are no regions of extended continuum emission in the studied region that could be used to measure absorption lines. In addition to studying known sources, searches for new OH maser sources were carried out, leading to the discovery of 22 new sources.

Studies of maser sources emitting in water-vapour lines at 1.35 cm in active star-forming regions were begun in 1979. A 96-channel spectral analyser with high spectral resolution was constructed at GAISH for this purpose. Observations of star-forming regions in different molecular lines (OH and $H_2O$) enable the investigation of different stages in the star-formation process. The 1.35-cm observations were carried out using the 22-m FIAN radio telescope in Pushchino. The variability of more than 60 $H_2O$ maser sources was studied in collaboration with R. L. Sorochenko of FIAN. Together with sources related to active star-forming regions were maser sources associated with variable infrared stars (giants and supergiants), which were in a late stage of stellar evolution.

In addition to their studies of maser sources, the spectral group of GAISH (Lekht, Pashchenko, Rudnitskii) carried out searches for radio recombination lines of hydrogen and carbon at metre wavelengths ($\lambda = 3$ m). Observations of Sagittarius A, Omega, W 51 (searches for hydrogen lines) and Cassiopeia A (searches for carbon lines) were conducted using the DKR-1000 and Large Scanning Antenna of FIAN. These observations provided upper limits for this line emission that enabled refinement of the parameters of these sources and the construction of models for gaseous clouds they might contain.

**Studies of Long-Wavelength Radio Emission** The research begun by Kardashev and Slysh in the 1960s was successfully continued in the 1970s under the supervision of V. P. Grigorieva. These studies were carried out at 50–2000 kHz, and were aimed primarily at investigating type II and type III solar radio outbursts, which arise in the solar corona and in interplanetary space during the propagation of shock waves and streams of electrons with energies of 10–1000 keV. Since the radio emission associated with these processes drifts in frequency, receivers with several frequency channels are required for such studies.

A multi-channel device developed at GAISH was installed on satellites of the *Prognoz* (*Prognoz-1*, *2*, *3*, *4*, *5*, *8*) and *Luna* (*Luna-11*, *12*, *22*) series. Observations of type-II outbursts were used to reconstruct the distribution of shock-wave velocities in the corona and interplanetary medium at distances from the Sun of 10 solar radii to the Earth's orbit. The kinetic temperature of the gas in these shocks and the brightness temperature of the radio emission from regions of plasma turbulence were derived. A correlation was found between the brightness temperature and velocity of the shock waves. Observations of type-II outbursts over many years were used to compare the parameters of the associated shock waves at different phases of the solar activity—the first time such a comparison was done. The distribution of electron velocities was derived from observations of type-III outbursts. All these studies provided input for models of the distribution of the electron density in the corona and interplanetary medium.

**Moving into the Millimetre and Submillimetre Bands** Zabolotnii at GAISH continued to work on pushing into these wavebands in the 1970s. In 1972–1975, he and V. F. Vystavkin (Institute of Radio Physics and Electronics) developed a high-sensitivity, broadband millimetre radiometer whose operation was based on the Josephson effect. Observations using this radiometer were carried out on the 22-m radio telescope of the Crimean Astrophysical Observatory in 1976. The first submillimetre (at wavelengths of 350 and 450 micron) observations in the Soviet Union were conducted in 1975, at the High Mountain Station of GAISH at Zailiiskii Alatau, at an elevation of about 3000 m above sea level. The opacity of the atmosphere at 350–450 micron was measured, and the possibility of conducting successful ground-based astronomy observations at these wavelengths under high-mountain conditions demonstrated. Unfortunately, these studies did not receive the necessary support from GAISH, and this line of research had to be ceased, with the result that Zabolotnii moved to IKI.

**Theoretical Studies** Theoretical research in radio astronomy at GAISH was carried out by Shklovskii, Pikel'ner and Kuril'chik. The results obtained by Shklovskii in the 1970s are described above.

Pikel'ner's studies associated with the interpretation of observational data for small-scale inhomogeneities in gaseous nebulae stand out as being among his most important work from this period. In 1973, he and Sorochenko (FIAN) deduced (based on optical and radio data) the presence of numerous small clumps of gas with electron densities of $10^4$ cm$^{-3}$ in the Orion Nebula. Pikel'ner suggested that these clumps originated due to the compression of initial fluctuations by shock waves arising during the deceleration of stellar winds.

Beginning in the 1960s, Pikel'ner was very interested in questions related to solar magnetohydrodynamics, and, more generally, a wide spectrum of problems in solar physics. His fundamental ideas in this area were generalised in the 1977 book *Physics of the Plasma of the Solar Atmosphere*, which he wrote in collaboration with Kaplan and V. N. Tsytovich. It is interesting that his studies of type-II solar radio outbursts led Pikel'ner to broader investigations of the interactions of shock waves in plasma, which he studied intensively together with Tsytovich in the 1960s and 1970s, as applied to both solar physics and the interstellar medium.

Kuril'chik carried out theoretical research in two areas: (1) statistical studies of the observed parameters of extragalactic sources and (2) the development of models for radio sources. The models he developed describe various structures that can be distinguished in radio sources and the phenomena occurring in them. For example, he constructed a model for the circum-nuclear structures responsible for the variable and "background" (quasi-stationary) components of the centimetre-wavelength radio emission. He also constructed a model for the structures displaying the characteristic variability observed at decimetre wavelengths, as well as other models. Kuril'chik's new interpretation of the jet in the radio galaxy Virgo A is of considerable interest. In this interpretation, based first and foremost on polarisation data, the optical and radio knots are due to anisotropic radiation from flows of particles in loops of magnetic field within the overall bipolar configuration.

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