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A Brief History of Radio Astronomy in the USSR

A Collection of Scientific Essays

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A Brief History of Radio Astronomy in the USSR

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Cover illustration: DKR-1000 cross radio telescope of Lebedev Physical Institute (FIAN): East–West arm

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Preface to English Edition

As was the case in Western countries, experimental radio astronomy in the Soviet Union largely grew out of wartime radar research programs. However, unlike in Europe, Australia, and the United States where post-war research was implemented primarily in universities and in civilian research laboratories, in the USSR any research with potential military application, such as radio and radar astronomy remained largely within military-oriented and tightly controlled laboratories. As such, publication in the open literature was restricted, and when published, important experimental details were usually omitted, so the results were often suspect or ignored by the Western scientific community. Thus, although starting in 1958, many of the most important Soviet journals were translated into English, for the most part Soviet observational radio astronomy had little impact outside of the Soviet Union. By contrast, the theoretical work of Soviet scientists such as Iosif Shklovskii, Solomon Pikel'ner, Vitaly Ginzburg, Yakov Zel'dovich in Moscow and Victor Ambartsumian in Armenia and later their students, including Nikolai Kardashev, Igor Novikov, and Vyacheslav Slysh, at the Sternberg Astronomical Institute, Yuri Pariiskii in Lenningrad, and Rashid Sunyaev at the Institute of Applied Mathematics was widely recognised and considerably influenced both theoretical thinking as well as motivating new observational radio astronomy programs in the United States, Australia, and Europe. Indeed, during the 1960s, Shklovskii's book, "Cosmic Radio Waves"[1] was widely used throughout the world by students of radio astronomy.

Radio astronomy in the USSR began with the work of Ginzburg[2] and Shklovskii[3] who independently derived the high temperature of the solar corona in 1946. Interestingly, although they were both theoreticians throughout their careers, both Ginzburg and Shklovskii travelled to Brazil as part of an early Soviet expedition to study the sun during the total eclipse of May 20, 1947. Although beleaguered by the death of expedition head, N.D. Papaleksi, just a few months prior to the eclipse and

[1]Shklovskii, I., *Cosmic Radio Waves,* Harvard University Press, Cambridge Massachusetts (1960).

[2]Ginzburg, V.L., 1946, Dokl. Akad. Nauk SSSR, 52, 487.

[3]Shklovskii, I.S., 1946, Astron. Zhur. 23, 333.

delayed an unusually late thawing of the winter ice their Latvian port, S. E. Khaikin and B. M. Chikhachev[4] succeeded in showing that, as predicted by Shklovskii and Ginzburg, the radio emission from the sun came from the much larger corona and not from the eclipsed solar disk (Sect. 1.1).

The early observational radio astronomy programs in the USSR were carried out primarily by people trained in physics or engineering. Many different Soviet laboratories were engaged in radio astronomy, and there was often significant competition among laboratories both for recognition and for resources. With a few exceptions, there was relatively little interaction between these radiophysicists and the more traditional Soviet astronomical community. Observational radio astronomy in the USSR was highly organised under the Scientific Council for Radio Astronomy of the USSR Academy of Sciences, for many years under the leadership of Academy Vice-President Vladimir Kotel'nikov. The main programs were centred at Lebedev Physical Institute (FIAN) (Chap. 1) with field stations in Crimea and later in Pushchino near Moscow, at the Main Astronomical Observatory in Pulkovo[5] (GAO) near Leningrad (Chap. 4), and at the Radio-Physical Research Institute (NIRFI) in Gorkii (Chap. 2) as well as at the Ukrainian Institute of Radio Physics and Electronics in Kharkov (Chap. 8). Skilled scientists, such as Vsevolod Troitskii in Gorkii, Viktor Vitkevich at FIAN, Semen Khaikin in Pulkovo, and Semen Braude in Kharkov often working with less than state-of-the art instrumentation made a number of important investigations. Somewhat later their students including Yuri Pariiskii in Pulkovo, Genadii Sholomitskii at Sternberg Astronomical Institute along with Arkadii Kuz'min, Roman Sorochenko and Leonid Matveenko at FIAN became the next generation of leaders. However, partly due to the different research cultures, as well as to the poor communication across the "Iron Curtain," to this day, their work has had little impact outside of the USSR. The translation of *A Brief History of Radio Astronomy in the USSR*, for the first time makes available in the English language, descriptions of the antennas and instrumentation used in the USSR, the astronomical discoveries, as well as interesting personal backgrounds on many of the early key players in Soviet radio astronomy.

For example we can read in Sects. 1.3 and 4.4 of the discovery of radio recombination lines by two independent laboratories at FIAN[6] and in Pulkovo[7] in 1964 and perhaps as early as 1963, although this important discovery is usually credited to Hoglund and Mezger[8] who reported the detection of the hydrogen 109α line in 1965 from a number of HII regions using the newly completed 140-ft radio telescope in Green Bank, WV. As this was the first important result from the 140-ft radio telescope, which along with a series of follow-up observations, rescued the

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[4] Khaikin, S.E. and Chikhachev, B.M., 1947, Dokl. Akad. Nauk SSSR, 58, 1923.

[5] Pariiskii, Y.N., 2007, Astron. Nach., 328, 405.

[6] Sorochenko, R.L. and Borodzich, E.V., 1965, Dokl. Akad. Nauk SSSR, 163, 603; 1966, Soviet Phys. Dokl., 10, 588.

[7] Dravskikh, A.F., Dravskikh, Z.V., Kolbasov, V.A., Misez'hnikov, G.S., Nikulin, D.E., and Shteinshleiger, V.B., 1965, Dokl. Akad. Nauk 163, 332; 1966, Soviet Phys.-Dokl., 10, 627.

[8] Höglund, B. and Mezger, P.G., 1965, Science 150, 339.

reputation of the 140-ft antenna as well as the Green Bank Observatory following a lengthy expensive construction period, it was perhaps convenient to ignore the earlier Soviet result.

The possibility of observing large *n* transitions in atomic hydrogen was discussed as early as 1945 by Henk van de Hulst[9] in his now famous paper which also discusses the 21 cm hyperfine structure line from atomic hydrogen, almost as an afterthought to the more extensive discussion of free-free and recombination line emission. However, van de Hulst erroneously concluded that due to Stark broadening, radio recombination lines would not be observable. Thus, although suitable equipment existed in many laboratories around the world, it wasn't until 1958 when Nikolai Kardashev[10] published an independent analysis showing that the effects of Stark broadening may have been previously over estimated, were there any serious attempts to detect radio recombination lines. The successful independent detections of the H90α line at 8872.5 MHz by Roman Sorochenko and Eduard Borodzich using the FIAN 22-m radio telescope in Pushchino and the 104α line at 5763 MHz by Alexander Dravskikh et al. at the Main Astronomical Observatory in Pulkovo were first reported at the XII IAU General Assembly in Hamburg, Germany in August 1964. Due to travel restrictions, the papers were presented by Yuri Pariiskii and Viktor Vitkevich, respectively. However owing to a combination of language difficulties, the poor quality of the visual material, the very restricted information about the instrumentation used that was permitted by the Soviet authorities, and the social isolation of the Soviet participants from the Western radio astronomy attendees resulting from their carefully monitored activities, the Pulkovo and Pushchino discoveries were widely discounted outside the USSR. However, in mid 1980's, in recognition of this important discovery, a team, including Sorochenko, Kardashev, Borodzich, and Alexander and Zoya Dravskikh received the USSR State Prize, one of the highest marks of recognition in science in Former Soviet Union.

As discussed in Sect. 3.2, a similar situation occurred following the 1965 discovery of radio source variability by Genadii Sholomitskii, who was then a young Moscow University graduate student of Shklovskii. At the suggestion of Shklovskii, Sholomitskii used the Crimean deep space tracking antenna system near Evpatoria to discover radio variability at 30 cm wavelength with a period of about 100 days in the well known peculiar quasar CTA 102. Sholomitskii's discovery was announced in an Astronomical Telegram[11] and in a short paper in the Astronomiicheskii Zhurnal[12] which generated considerable attention in the West, but for several reasons this unexpected result was generally discounted by Western radio astronomers. First, apparently for security reasons, no experimental details were given in the published papers to substantiate the claimed results, although a picture of an unfamiliar antenna system was shown in the main Soviet daily newspaper, Pravda, which did

[9] Van der Hulst, H., 1945, Nederlandsch. Tijdschr. V. Natuurkunde 11, 201, see also Sullivan.

[10] Kardashev, N., 1959, Astron. Zh., 36, 838; Soviet Astron.-AJ, 3, 813.

[11] Sholomitskii, G.B., 1965, IAU Information Bulletin on Variable Stars, 83, 1.

[12] Sholomitsky, G.G., 1965, Astron. Zh. 42, 673; Soviet Astron.-AJ 9, 516.

arouse considerable interest within Western intelligence circles. Secondly, observations at several Western observatories did not show any evidence for radio variability in CTA 102 or any other radio source. Finally, and perhaps most important, it was understood by everyone, including the members of Shklovskii's group, that such rapid variability was "theoretically impossible" since light travel time arguments meant that the source would need to be so small, that any radio emission would be self absorbed.

Indeed, the theoretical objections appeared so compelling, that at a press conference at the Sternberg Institute, Kardashev half jokingly suggested that perhaps the radio emission from CTA 102 might be a transmission from an extraterrestrial intelligence. This was reported on the front page of Pravda, and was picked up by newspapers around the globe, further detracting from the credibility of the claimed variability. It was not until a few years later, when Bill Dent[13] reported observing radio variability at the University of Michigan Radio Observatory, that the phenomena of radio variability was accepted. We now know that the radio emission from CTA 102 does vary at 30 cm on the time scales reported by Sholomitskii, as do many other quasars, and that this phenomena is now understood to occur as a combination of relativistic beaming and interstellar scattering.

One Soviet observational program which was widely recognised, was the series of experiments to establish an accurate flux density scale for discrete radio sources. Although the measurement of the relative strength of discrete radio sources is straight forward, one of the outstanding challenges in experimental radio astronomy is the absolute calibration of the discrete source flux density scale. As described in Sect. 2.2.2, V. Vsevolod Troitskii and his colleagues in Gorkii carried out a series of elegant experiments using an "artificial moon" as a black body standard reference source. The results of this work on absolute calibrations were subsequently used throughout the world to calibrate relative measurements made with other facilities.

Chapter 9 discusses the planetary radar program led by Academician Vladimir Kotel'nikov which was closely coupled to the Soviet space program. Unlike the passive radio astronomy program, perhaps heightened by the existing cold-war competition, there was an intense rivalry between the Russian and American attempts to be the first to detect radar reflections from the planet Venus. The prize was not only scientific priority, but the accurate determination of the Astronomical Unit important for planned missions to Venus and Mars by both the USSR and the US. But the account given in Chap. 9 makes only passing reference to the earlier work at the Goldstone and Millstone Hill facilities in the US. Indeed, the initial Russian announcement of the value of the AU based on their 1961 measurements was remarkably close to the value that had been previously announced by Goldstone which was later recognised to be based on a spurious detection from Venus.

Section 1.3 discusses the 1962 suggestion by Leonid Matveenko on building an independent-oscillator-tape-recording interferometer which could allow the unlimited extension of interferometer baselines to gain extraordinary high angular resolution. No attempt was made to implement this new technique, probably due to the

[13]Dent, W., 1965, Science 148, 1458.

lack of suitably instrumentation in Russia, and the combination of Soviet bureaucracy and secrecy delayed publication of these ideas until 1965.[14] However, by this time programs were already underway in the US and Canada to implement these techniques for Very Long Baseline Interferometry. Apparently, there was some discussion with A.C.B. Lovell and Henry Palmer to develop a radio interferometer between Russia and Jodrell Bank, but nothing ever materialised from these discussions. Much later, Matveenko and others collaborated with US radio astronomers to implement independent-oscillator tape-recording interferometry between Crimea and the United States.[15] For over three decades, Russian radio astronomers, led by Academician Kardashev, have been preparing a satellite known as “RadioAstron” to go into very high orbit to enable very long baseline interferometer observations in conjunction with ground-based radio telescopes in many countries to increase the resolution over purely ground based observations by more than an order of magnitude.[16]

Outside of Russia, the most influential Soviet radio astronomy observations were based on the low frequency arrays developed by Simon Braude and later by Leonid Litvinenko and Alexander Konovalenko near the Ukrainian city of Kharkov (Chap. 8). For many years this was the most powerful facility in the world working at decameter wavelengths. Braude and his colleagues carried out a number of interesting programs on radio source spectra and high n recombination lines, but their work was plagued by the absorption and distortions which took place in the ionosphere. Only recently, with the development of sophisticated digital technology and high speed computing, are these problems being successfully attacked by the new generation of low frequency radio telescopes in Europe, the US, and in Australia which are building on the pioneering work begun at Kharkov.

It is clear from many of the accounts reported in this book that many Soviet radio astronomers appeared as unfamiliar with Western radio astronomy programs as were Western scientists about the Soviet work. Due to hard currency restrictions in effect at the time, Western journals and books were routinely copied in the USSR and were widely distributed throughout the country. However, this meant very long delays between the time of publication and when the journal became available to individual scientists. While the academic astronomers, for example at the Sternberg Institute, had a good reading knowledge of English, the observational radio astronomers, who were primarily educated as engineers, were less comfortable with English, and may not have carefully followed the foreign literature.

Perhaps because of their lack of contact with Western radio astronomers, Soviet scientists were slow to pick up the growing trend in the 1960s and 1970s to build large arrays of modest sized dish antenna such as the Westerbork Array, the VLA, and the Australia Telescope Compact Array. Instead, concerned about phase stability problems inherent in multi-element interferometer arrays, and not having

[14] Matveenko, L.I., Kardashev, N.S. and Sholomskii, G.V., 1965, Radiophysica, 8, 651; Soviet Radiophysics, 8, 461.

[15] Matveenko, L.I., 2007, Astron. Nach. 328, 411.

[16] Kardashev, N.S., 1999, Experimental Astronomy, 7, 329.

access to the computing facilities needed to analyse multi-element interferometer data, the Russians concentrated on large one dimensional filled aperture standing arrays or phased arrays, such as the Pulkovo antenna designed by Khaikin, and later the RATAN-600 antenna, (Chap. 4) neither of which made a big impact to radio astronomy outside the Soviet Union. The 22-m steerable radio telescope located in Pushchino, near Moscow, and its twin even more accurate, version built in Crimea on the shores of the Black Sea were, however, the first radio telescopes of their size to operate at millimetre wavelengths (Sect. 1.3). Both the Pushchino and Crimean antennas were used for some of the earliest radio observations at millimetre wavelengths, especially of the planets, but their impact was limited by the poor sensitivity of the receivers available to the Soviet radio astronomers. The Crimean antenna was used in 1969 for the first VLBI observations between the USSR and the US,[17] and later, it was used together with the European VLBI Network.

As already mentioned, Soviet theoretical work had a much greater impact in the West than the observational programs. Probably the most productive theoretical programs were those led by Shklovskii at the Moscow State University Sternberg Astronomical institute (GAISH) and later at Space Research Institute (IKI) and Ginzburg at the Lebedev Physical Institute (FIAN). Ginzburg's contributions to basic synchrotron radiation theory[18] had a big impact in the West, including his two extensive articles in the Annual Reviews of Astronomy and Astrophysics[19,20] which form the basis for our current interpretation of the synchrotron radiation from radio galaxies and quasars. Similarly the pioneering work on the early universe and large scale cosmic structures by Zel'dovich, and later his young collaborators Igor Novikov and Rashid Sunyaev was well known throughout the world and continues to this day to influence current thinking.

Shklovskii and his close group of students, who were first part of GAISH and later were located at the Space Research Institute (IKI), were arguably the world's outstanding theoretical group in radio astronomy (see Chap. 3). They not only provided innovative interpretations of the plethora of new observational discoveries being made in Europe, Australia, and the United States, but perhaps more important they predicted a number of new phenomena that could be observationally tested. Unlike their observational counterparts in the USSR, the GAISH/IKI group was well informed about what was happening outside the USSR. They were a valuable part of the international radio astronomy community and they traded letters and where possible personal visits. Shklovskii, along with his students, Slysh and Kardashev, applied the synchrotron theory to interpret the radio emission from supernovae[21] and

[17] Broderick, J.J. et al. 1970, Astron. Zhur. 47, 748; Soviet Astron.-AJ, 14, 627.

[18] Ginzburg, V.L., 1951, Dokl. Akad. Nauk, 76, 377; in Classics in Radio Astronomy, ed. W.T. Sullivan III (Reidel), p. 93.

[19] Ginzburg, V.L. and Syrovatskii, S.I., 1965, ARAA, 3, 297.

[20] Ginzburg, V.L. and Syrovatskii, S.I., 1969, ARAA, 7, 1969.

[21] Shklovskii, I.S., 1960, Astron. Zhur. 37, 256; Soviet Astron.-AJ, 4, 243.

radio galaxies[22,23] which motivated many new observational programs. Particularly important were Shklovskii's prediction of the M87 polarisation,[24] his prediction of the 2% per year flux density decay of the Cas A supernova remnant,[12] his calculation of the HI,[25] Deuterium,[26] OH and CH[27] line frequencies, Slysh's interpretation of the peaked spectrum radio sources CTA 21 and CTA 102 as due to synchrotron self absorption,[28] Kardashev's explanation of radio source spectra as the result of synchrotron radiation cooling,[29] and as mentioned above, his classical paper on radio recombination lines.[6] Interestingly, Shklovskii's group appeared to have little or no access or need of computers, and their analysis was characteristically reduced to simple problems that could be worked analytically. Although Shkovskii's work was widely recognised in the West, unlike his counterparts Ginzburg, Zel'dovich, and Ambartsumian, Shklovskii was never elected as a full Member of the Soviet Academy of Sciences. An account of Sklovskii's life is told in his entertaining autobiographical book, *Five Billion Vodka Bottles to the Moon: Tales of a Soviet Scientist*.[30]

Section 3.4 reports on the prescient 1964 paper by Igor Novikov and Andrei Doroshkevich[31] which predicted the existence of a cosmic microwave background (CMB) that could have been experimentally tested. Novikov and Doroshkevich were sufficiently familiar with the Western literature to realise that a relevant experiment in the United States had been previously reported by E.A. Ohm in the Bell System Technical Journal.[32] However, it remained for Penzias and Wilson,[33] who were unaware of the Novikov and Doroshkevich paper or even the Ohm paper from their own laboratory, to discover the CMB the following year and relate it to the big-bang early universe. As reported in Sect. 4.4, as early as 1959, T. Shmaonov, working at the Pulkovo Observatory, may have marginally detected the CMB as part of his PhD research using a horn antenna at 3.2 cm. However, no one in the USSR or elsewhere related this to the CMB until after learning of the Penzias and Wilson paper.

For many years Russian scientists were leading the Search for Extraterrestrial Intelligence (SETI). Kardashev's classic 1963 paper on so-called Type I, Type II,

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[22] Shklovskii, I.S., 1962, Astron. Zh., 39, 591; 1963; Soviet Astron.-AJ, 6, 465.

[23] Shklovskii, I.S., 1963, Astron. Zhur., 40, 972; 1964, Soviet Astron.-AJ, 7, 748.

[24] Shklovskii, I.S., 1955, Astron Zhur., 32, 215.

[25] Shklovskii, I.S., 1949, Astron. Zh. 26, 10.

[26] Shklovskii, I.S., 1952, Astron. Zh. 29, 144.

[27] Shklovskii, I.S., 1949, Dokl. Akad. Nauk, 92, 25.

[28] Slysh, V., 1963, Nature 199, 682.

[29] Kardashev, N.S., 1962, Astr. Zhur. 39, 393; 1962, Soviet Astron.-AJ 6, 317.

[30] Shklovskii, I.S., 1991, Five Billion Vodka Bottles to the Moon: Tales of a Soviet Scientist (W.W. Norton & Company).

[31] Doroshkevich, A.G. and Novikov, I.D., 1964, Dokl. Akad. Nauk, 154, 809.

[32] Ohm, E.A., 1961, Bell System Technical Journal, 40, 1065.

[33] Penzias, A.A. and Wilson, R.W., 1965, ApJ 142, 419.

and Type II civilisations[34] continues to define observational SETI programs, while Shkovskii's book[35] after translation to English with Carl Sagan as a co-author became a standard reference on SETI.[36] Section 3.3 describes how the interest in pursuing an observational SETI program, led in part to the establishment of the RATAN-600 radio telescope which, since 1976, has continued to be the most powerful radio astronomy facility in Russia.

In spite of the tensions between the USSR and Western countries, scientific exchanges between the two countries began in the early 1960s. In 1961, a group of Soviet and American astronomers met in Green Bank, WV to discuss various topics in radio astronomy. In 1964, Arkadii Kuz'min from FIAN spent a year at Caltech working with Barry Clark to make interferometric studies of the planet Venus[37] which provided important guidance to the planning of both U.S. and Soviet missions to Venus. Later George Swenson (University of Illinois) and Ron Bracewell (Stanford) participated in an exchange visit to the Soviet Union. Long term visitors to the USSR included Malcolm Longair from the Cavendish Laboratory who worked closely with Zeldovich and his group, and later, Denise Gabuzda who very ably translated this volume and who worked at FIAN from 1994 to 1998, and who continues to work with both Russian graduate and undergraduate students. Starting in 1969, Russian and US radio astronomers began a collaboration in Very Long Baseline Interferometry which later included observations between European radio telescopes and the growing network of Russian radio telescopes.[14,38]

Following the difficult economic times after fall of the Soviet Union in 1991, radio astronomers from the Former Soviet Union have become more integrated with their Western counterparts with greatly improved communication and increasing ease of movement between Russian and Western scientists and students.

Unfortunately, *A Brief History of Radio Astronomy in the USSR* does not give citations to many of the original works which would have greatly added to the value of the book. Therefore, some key references are given in this section for readers that wish to learn more about early radio astronomy in the USSR. More detailed reports of early Soviet era observational and theoretical radio astronomy can be found in W.T. Sullivan's books, *The Early years of Radio Astronomy*[39] and *Cosmic Noise.*[40]

I am indebted to Denise Gabuzda, Leonid Gurvits, Yuri Kovalev, Malcolm Longair, and Leonid Matveenko, and Woody Sullivan for clarifying many points relat-

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[34] Kardashev, N., 1963, Astr. Zh. 41, 2; 1964, Soviet Astronomy-AJ, 8, 217.

[35] Shklovskii, I.S., *The Universe, Life, and Intelligence*, USSR Academy of Science, Moscow (1961).

[36] Shklovskii, I.S. and Sagan, C., *Intelligent Life in the Universe,* Holden-Day, San Francisco (1966).

[37] Clark, B. and Kuz'min, A.D., 1964, ApJ, 142, 23.

[38] Kellermann, K.I., 1992, in Astrophysics on the Threshold of the 21st Century, ed. N.S. Kardashev (Gordon and Breach), pp. 37–51.

[39] Sullivan III, W.T. 1984, The Early years of Radio Astronomy, Cambridge University Press, pp. 268–302.

[40] Sullivan III, W.T. 2009, Cosmic Noise, Cambridge University Press, pp. 214–221, 380–384.

ing to the history of radio astronomy in the Former Soviet Union. Leonid Gurvits, Yuri Ilyasov, Leonid Lytvynenko, and Leonid Matveenko provided high resolution copies of many of the illustrations which are reproduced in this English edition, in place of the poor quality originals Russian volume. In some cases, for clarity, we have substituted, similar, although not identical, illustrations when there was no adequate version of the original.

Charlottesville, VA, USA K.I. Kellermann

Preface

The first results of observations of radio waves arriving at the Earth from the cosmos were published in 1932. These observations, which were carried out at the end of 1931 by the American engineer Karl Jansky, who was studying radio interference at 14.6 m, marked the birth of radio astronomy.

The 50th birthday of radio astronomy led to a growth in interest in both radio astronomy results and the history of the birth and development of this new scientific field.

Radio astronomy began to be intensely developed only after the end of the second World War, when research in radar and radio communications led to the development of the technical equipment needed for radio astronomy observations. However, even in the pre-war years, the well known Soviet physicists Academicians L. I. Mandel'shtam and N. D. Papaleksi had thought about the possibility of radar observations of the Moon.

Radio astronomy research in the Soviet Union began to be developed starting in 1946–1947. Thus, the 50th anniversary of the birth of radio astronomy essentially coincides with the 35th anniversary of its development in the USSR. In connection with this, the Scientific Council for Radio Astronomy of the Academy of Sciences of the USSR, headed by Academician V. A. Kotel'nikov, delegated a group of radio astronomers the task of preparing a publication outlining the history of the development of radio astronomy in the Soviet Union.

Radio astronomy is, naturally, a subfield of astronomy. Accordingly, one could lay out the history of its development following the division of astronomy into studies of various types of objects: radio astronomy of the solar system, of Galactic objects, of extragalactic objects, etc. However, because radio astronomy information about the Universe is obtained via measurements of radio emission arriving from the cosmos using radio physical techniques, it would also be reasonable to lay out such a history according to a different scheme: describing the history of radio telescope and radio receiver construction, the development of radio interferometry, spectral radio astronomy, radar astronomy, out-of-atmosphere radio astronomy, and so forth.

It would clearly be very difficult to write a monograph following either of these schemes within a rather compressed time schedule. In addition, it would be difficult to reflect in such a monograph various interesting details of the establishment and development of radio astronomy studies in various scientific groups across the country. Therefore, it was decided to first prepare a collection of essays, in which the pioneers of radio astronomy themselves or their close coworkers and students would describe the history of the development of radio astronomy research within their own institutes.

Of course, the writing of such a collection did not exclude, and more likely stimulated, the writing of various memoirs, such as the leaflet by Corresponding Member of the Academy of Sciences I. S. Shklovskii [1] or the article on Adacemician V. L. Ginzburg [2] published in 1982. The proposed collection was meant to, in part, supplement such previously published reviews, dedicated to the early period and results of the development of Soviet radio astronomy [3, 4, 5, 6].

When compiling the collection, the choice of a standard for citations proved to be a serious problem. The huge number of references for a book of limited volume precluded the inclusion of a comprehensive bibliography. We settled on a format in which the descriptions of the methods and results are accompanied only by an indication of the relevant authors and, as a rule, the publication date for the corresponding work. This supposes that the reader can find more detailed information using compilations of references, such as [7, 8].

It was considered necessary to allocate at least a little space in the collected essays to biographical information about the founders of Soviet radio astronomy who are deceased—N. D. Papaleksi, S. E. Khaikan, V. V. Vitkevich, G. G. Getmantsev, S. A. Kaplan, S. I. Syrovatskii, S. B. Pikel'ner, B. M. Chikhachev, M. M. Kobrin, D. B. Korol'kov.

When examining the history of the development of radio astronomy in the Soviet Union as a whole, we can mark several successive stages. The first began in 1946 with the theoretical work of V. L. Ginzburg and I. S. Shklovskii, radio observations of the solar eclipse of 1947 carried out by S. E. Khaikin and B. M. Chikhachev at the initiative of N. D. Papaleksi, the work of radio physicists in Gorkii under the supervision of M. T. Grekhovaya and G. S. Gorelik. This first stage continued until roughly the middle of the 1950s. At that time, primarily in relation to solving important applied problems having to do with the propagation of radio waves through the Earth's atmosphere, the first generation of Soviet radio telescopes, radio interferometers and radiometric receivers operating at a wide range of wavelengths from 4 m to 2 cm was created (partly based on radar technology), and the first series of radio observations of the quiescent and perturbed Sun, the Moon and the brightest discrete cosmic radio sources were carried out.

Astrophysical studies of fundamental importance were carried out in this stage, which opened possibilities for the development of a number of new directions in radio astronomy. As in all subsequent stages, a huge role in the development of Soviet radio astronomy was played by fundamental theoretical studies of the physics of the Sun, planets, interstellar medium, cosmic rays, supernova remnants, galactic nuclei, extragalactic objects and the expanding Universe (at the Sternberg Astronomical Institute of Moscow State University [GAISH], Lebedev Physical Institute of the USSR Academy of Sciences [FIAN], Institute of Applied Mathematics of the USSR Academy of Sciences [IPM], Byurakan Astronomical Observatory of the Academy of Sciences of the Armenian SSR [BAO], and the Radio Physical Research Institute in Gorkii [NIRFI]). These studies served as the main program for carrying out observations and interpreting the results obtained. Fundamentally new methods that are now in wide use in the world of radio astronomy were proposed in this period.

Among the important results of this first stage, we should note the discovery of the supercorona of the Sun by V. V. Vitkevich (FIAN), the discovery of the linear polarisation of the diffuse cosmic radiation (NIRFI), the detection of circular polarisation of the radio emission of active regions on the Sun (Main Astronomical Observatory of the USSR Academy of Sciences in Pulkovo [GAO]), and the detection and study of the spectra of thermal and non-thermal sources at centimetre wavelengths (FIAN, NIRFI, GAISH).

The second stage is marked by the construction of large-scale radio telescopes operating in various wavelength ranges (metre, centimetre and millimetre), especially for the needs of the radio astronomy community: the Large Pulkovo Radio Telescope; the fixed 31-m radio telescope of FIAN in the Crimea; the fully steerable, precise 22-m radio telescope of FIAN in Pushchino, and then the 22-m radio telescope of the Crimean Astrophysical Observatory [CrAO] in Simeiz; the DKR-1000 wide-band cross radio telescope of FIAN; the Large Radio Interferometer of the BAO and the compositive eight-element antenna of the Deep Space Communications Centre in the Crimea. Very important studies of the radio emission of the Moon were carried out in this stage, which made it possible to determine a number of characteristics of its surface layers using radio astronomy methods (NIRFI, FIAN), and to detect a previously unknown heat flux from the lunar core (NIRFI). Radio "images" of the Sun and Moon were obtained at centimetre and millimetre wavelengths, including the polarisation of the radiation (FIAN, GAO), and ejections of solar material with speeds exceeding the escape speed were detected (FIAN). The radio emission of Venus and some other planets was studied, and the presence of a high surface temperature on Venus was established (FIAN, GAO). Unique investigations of the fluxes and polarisations of discrete radio sources were conducted, in particular, of the Crab Nebula (FIAN, GAO, GAISH, BAO), and work that ultimately led to the discovery of the variability of extragalactic radio sources was begun (GAISH).

In this stage, methods for precise, absolute measurements were developed, and an accurate catalogue of the fluxes of powerful discrete sources was compiled (NIRFI). The spectra of many sources were measured over a broad range from centimetre to decametre wavelengths (GAO, FIAN, the Institute of Radio Physics and Electronics of the USSR Academy of Sciences [IRE], GAISH and others). Methods for measuring the brightness distributions of sources using scintillation observations and the "coverage" method were refined.

The results of these and other measurements made it possible to lay the basis for a number of theories, such as those describing the magnetic bremsstrahlung mechanism for the radio emission of solar active regions (FIAN, GAISH, GAO, NIRFI), the thermal radio emission of the Moon and planets (NIRFI), the synchrotron and thermal radio emission in the continuous spectra of cosmic sources (FIAN, GAISH, NIRFI) and the radio lines of atoms and molecules (GAISH).

The vigorous development of Soviet radar astronomy made it possible, not only to refine knowledge of the astronomical unit, which was exceptionally valuable for astronautics, but also to determine a number of important characteristics of the planets (IRE and others).

At the beginning of the 1960s, theoretical and experimental work related to a new and promising direction began—the search for extraterrestrial civilisations using radio astronomy methods (GAISH, NIRFI, Special Astrophysical Observatory [SAO], BAO).

In the middle of the 1960s (the third stage), specialised areas in radio astronomy were widely developed. Radio recombination lines of excited hydrogen were discovered (GAISH, FIAN, GAO) and studies in this direction were developed. The fundamentally new method of Very Long Baseline Interferometry was proposed (FIAN, GAISH, GAO), and work was begun on its realisation (GAISH, FIAN, NIRFI, the Space Research Institute [IKI], BAO, CrAO, GAO).

At the end of the 1960s and beginning of the 1970s, Soviet radio astronomy received a new impulse in its development in connection with the construction of large radio telescopes, including the unique RATAN-600 telescope (SAO), the T-shaped UTR-2 radio telescope (IRE) operating at decametre wavelengths, the Large Scanning Antenna operating at metre wavelengths (FIAN) and the RT-25X2 transit radio telescope operating at millimetre wavelengths (NIRFI). The Simeiz–Pushchino interferometer was devised on the basis of the two corresponding 22-m antennas, and this system was used to successfully carry out Soviet and international VLBI experiments enabling the realisation of extremely high resolution (IKI, CrAO, FIAN).

In these years, Soviet radio astronomy also went beyond the limits of the Earth's atmosphere. In addition to studies at the longest wavelengths begun earlier (GAISH, NIRFI), the first experiments with parabolic antennas operating at submillimetre (FIAN) and centimetre (IKI) wavelengths on board orbiting, manned stations were carried out. Radio astronomy measurements of the characteristics of the surfaces and atmospheres of the planets and of the Earth as a planet were conducted on board automated spacecraft (IKI, IRE, FIAN).

Observations with high spatial resolution enabled the discovery of radio granulation on the Sun (GAO, SAO, CrAO, NIRFI, the Institute of Applied Physics of the USSR Academy of Sciences [IPFAN]), and the measurement of the temperature of the moons of Jupiter (FIAN, SAO, CrAO). Studies of the brightness distributions and polarisations of discrete sources were continued over a wide range of wavelengths (SAO, BAO). A number of sources were observed with high frequency resolution in spectral lines of hydrogen, hydroxyl, formaldehyde and water vapour (SAO, FIAN, GAISH, IKI). The first spectral radio lines at millimetre wavelengths were detected—radio recombination lines of hydrogen H56α (FIAN), and later, very low-frequency spectral lines—recombination lines of carbon with principle quantum numbers up to 630 (IRE).

The absence of fluctuations of the cosmic background radiation was established with high accuracy (SAO), in disagreement with all theories of fragmentation. Measurements of the intensity of the cosmic background radiation were carried out at a number of wavelengths (NIRFI, FIAN). Thousands of new radio sources were discovered at centimetre and decametre wavelengths (GAISH, SAO, IRE).

During the third stage, wide-ranging studies of pulsars were conducted at centimetre, decimetre, metre, and decametre wavelengths (FIAN, IRE, IKI), which led to the discovery of new sources and established a number of important properties in the structure of pulsar pulses.

The construction of the 70-m radio telescope of the Deep Space Communications Centre began in the Crimea at the beginning of the 1980s, on which radio astronomy investigations at wavelengths right down to 8 mm were initiated.

In this collection of essays, we can only make reference to all of the studies listed above.

In the 1950s, the Commission for Radio Astronomy was established in the Scientific Council of the USSR Academy of Sciences on Astronomy, under the chairmanship of S. E. Khaikin. Later (in 1961), this was transformed into the Scientific Council of the USSR Academy of Sciences on Radio Astronomy, whose permanent chairman is Academic V. A. Kotel'nikov. The Scientific Council on Radio Astronomy played and continues to play an extremely important role as a force unifying Soviet radio astronomers, in helping to realise large-scale scientific and technical projects, and in organising regular conferences that attract a large number of specialists in both radio astronomy and related fields. With the help of this Council, international collaborations have been developed between Soviet radio astronomers and their foreign colleagues, in which virtually every scientific institution working on radio astronomy problems in the Soviet Union participates.

Returning to the structure of this collection, we note that the arrangement of the contributions is fairly arbitrary. It is determined primarily by the time when radio astronomy studies began at the institutions involved. In recent years, both fundamental and applied radio astronomy have also developed in some organisations that are not directed represented in this collection. These include, for example, the Physical–Technical Institute of the Academy of Sciences of the TSSR, the Main Astronomical Observatory of the Academy of Sciences of the Ukrainian SSR, the Bauman Moscow Higher Technical Institute and some others. Works by researchers at these organisations are referenced in the corresponding contributions.

Radar studies of meteors in the USSR began in 1946 [4], and soon became a method for studying atmospheres. This method is not considered here.

In connection with the limited volume available, and also to avoid repetition in the material presented by the various scientific groups, the collection includes cross-references to other essays in the volume. For convenience in referencing, arbitrary identifying numbers are given in the headings to the essays.

The Editorial Group is grateful to all who took part in the creation of this collection, especially L. I. Matveenko and P. D. Kalachev, who looked over the manuscript and made valuable comments. We will also be thankful to any readers for comments that arise as they become acquainted with this collection.

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Chapter 1
Radio Astronomy Studies at the Lebedev Physical Institute

B.A. Dogel', Y.P. Ilyasov, N.L. Kaidanovskii, Y.L. Kokurin, A.D. Kuz'min, A.E. Salomonovich, R.L. Sorochenko, and V.A. Udal'tsov

Abstract The history of the development of radio astronomy studies at FIAN is described, beginning with the first theoretical (1946) and experimental (1947) studies of the solar radio emission. Information about the development of the Crimean station of FIAN, then the establishment and development of the Radio Astronomy Station in Pushchino is presented. Work on the construction of large radio telescopes, including the FIAN 22-m, DKR-1000 and BSA telescopes, is described, together with important results obtained during observations of the Sun (including the discovery of its "supercorona"), planets, line radio emission and studies of pulsars and other discrete sources.

1.1 The First Steps[1]

The important radio physicist Academician Nikolai Dmitrievich Papaleksi (Fig. 1.1) is justifiably considered the founder of radio astronomy research in the Soviet Union. Nikolai Dmitrievich was interested in astronomy and meteorology even in his youth. Before the Second World War, he and Academician Leonid Isaakovich Mandel'shtam considered the possibility of measuring the distance to the Moon using radar methods, by detecting the time delay of a radio pulse sent from the Earth and reflected off the lunar surface. The level of radio technology available at that time (1925) made this appear unpromising. Papaleksi and Mandel'shtam returned to this problem during the years of the Second World War. Their new calculations, published at the beginning of 1946, showed that such measurements were realistic, and indeed, they were carried out in that same year in Hungary and the USA. When it came to thinking of radar measurements of the Sun, Papaleksi gave the young theoretician of the Lebedev Physical Institute (FIAN) V. L. Ginzburg the problem of carrying out the necessary calculations.

[1]Section 1.1 was written by N.L. Kaidanovskii and A.E. Salomonovich, Sect. 1.2 by V.A. Udal'tsov, Y.L. Kokurin and R.L. Sorochenko, Sect. 1.3 by Y.P. Ilyasov, A.E. Salomonovich and A.D. Kuz'min, Sect. 1.4 by V.A. Dogel' and Sect. 1.5 by A.E. Salomonovich.

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DOI 10.1007/978-94-007-2834-9_1,

Fig. 1.1 Nikolai Dmitrievich Papaleksi (1880–1947)

Academician Ginzburg describes this occurrence as follows: “N. D. Papaleksi, naturally, had thought about radar measurements of the planets and Sun. In this connection, he asked me at the end of 1945, or more likely the beginning of 1946, to elucidate the conditions for the reflection of radio waves from the Sun. It stands to reason that, in essence, this was a typical ionospheric problem, and I had all the corresponding formulas to hand. The results of the calculations did not seem especially optimistic, since they indicated that, for a broad range of parameters, many of which were unknown then (the number density of electrons, the temperatures in the corona and chromosphere), radio waves should be strongly absorbed in the corona or chromosphere, so that they should not even reach the level where they would be reflected… But a more interesting conclusion followed directly from this: the sources of solar radio emission should not be in the photosphere, but instead in the chromosphere, or even in the corona in the case of longer waves. Further, it was already supposed at that time that the corona was heated to hundreds of thousands, or even a million, degrees. Thus, even under equilibrium conditions (in other words, in the absence of any perturbations), the temperature of the solar radio emission emitted by the corona (waves with wavelengths longer than about a metre) should reach about a million degrees for a photospheric temperature of 6000 degrees” [2, p. 289].

These results were laid out by Ginzburg in a paper published in the Reports of the Academy of Sciences in 1946. The conclusion that the corona must be the source of solar radio waves at metre wavelengths was also drawn nearly simultaneously and independently by I. S. Shklovskii in the Soviet Union and by D. Martin in England.

Papaleksi had also been interested earlier in the problem of solar–terrestrial connections, including the important question of the influence of solar activity on the Earth's ionosphere and the stability of radio communications. One of the methods he adopted was making observations during solar eclipses, when it was possible to distinguish the influences of the photon and particle fluxes from the Sun. During the eclipse of July 9, 1945, Papaleksi had already carried out a broad set of studies of phenomena in the ionosphere accompanying the eclipse. He intended to continue these investigations during the total solar eclipse of May 20, 1947, which it was possible to observe from Brazil. For this purpose, he began to prepare a large, multi-faceted expedition. Now, after the estimates of Ginzburg, it was planned for the first time to make not only ionospheric observations, but also direct observations of the radio emission of the Sun at metre wavelengths. Papaleksi hoped to detect not only the steady-state emission of the quiescent Sun, but also (thanks to the high resolution attained during eclipse observations) regions of sporadic radio emission. Information about this radiation obtained abroad during the war years was just starting to appear in literature at that time.

In a public lecture in January 1947, Papaleksi said the following about radio astronomy: "This new area of research, which is currently in its infancy, will undoubtedly be of extreme interest for physics of the Sun. There is every reason to believe that the application of radio astronomy methods in astronomy will open a new era, whose importance can be compared to the discovery of Fraunhofer lines and the application of spectral analysis in astrophysics, and which will help us penetrate more deeply into the mysteries of the Universe."

Radio observations of the Sun during partial eclipses began abroad starting in 1945, but these observations did not yield conclusive results. The total eclipse of May 20, 1947 could potentially provide important new information.

The Brazilian expedition was organised by the Scientific Council of the USSR Academy of Sciences on Astronomy under the supervision of Academician Papaleksi, who was then the Head of the Oscillation Laboratory of FIAN. The well known polar explorer G. A. Ushakov was the administrative assistant to the head of the expedition. The expedition included researchers from optical, radio astronomy and ionospheric groups. Papaleksi supervised the last two of these groups, and M. N. Gnevyshev the optical group.

In the period of preparation for the expedition, it was necessary to acquire and adapt all the equipment, develop the methods to be used for the observations, carry out the necessary calculations of the conditions for the eclipse and prepare a program for the reduction of the observations.

The expedition members included the now well known scientists V. L. Ginzburg and I. S. Shklovskii. The radio astronomy observations were to be carried out by Papaleksi's student B. M. Chikhachev (Fig. 1.2), formerly of the Central Radio Laboratory, who was an experienced specialist on radio technology and electronics. Before the Second World War, he had studied the technology of preparing metallic radio lamps in the USA, and, during the war, he was the chief technician at a radio factory. After the war, he became a PhD student of Papaleksi in FIAN. Workers under Academician A. I. Berg were assigned as assistants to Chikhachev. This group was responsible for the radio astronomy equipment for the expedition.

The planned observations of the radio emission of the Sun at a wavelength of 1.5 m required a radio telescope with a fairly high sensitivity, since, according to calculations, the intensity of the signal might be decreased by more than a factor of ten during the eclipse. An antenna with a large receiving area that was capable of tracking the Sun over the entire period of the eclipse (about three hours) was required, as well as a broad-band receiver with a good noise coefficient. A large

Fig. 1.2 Boris Mikhailovich Chikhachev (1910–1971)

number of Soviet and foreign radar equipment with suitable parameters were left after the war. A radar receiver operating at a wavelength of 1.5 m was selected for the eclipse observations.

However, Papaleksi was not able to realise his plan; he died suddenly on February 3, 1947. At a memorial service dedicated to N. D. Papaleksi in April 1947, the President of the Academy of Sciences Academician S. I. Vavilov said, "Death has claimed Nikolai Dmitrievich during his preparations for an expedition to Brazil, for which he and his students, as always, prepared meticulously and at the head of which he stood. He was not fated to live to see the realisation of this expedition, and now his orphaned students will sail on a Soviet ship to the shores of Brazil without their teacher.[2]"

The supervision of the expedition was given to Corresponding Member of the Academy of Sciences A. A. Mikhailov, and his scientific assistant and supervisor of the radio astronomy and ionospheric groups became Semen Emmanuilovich Khaikin (Fig. 1.3)—a student of L. I. Mandel'shtam, who can be considered a cofounder of Soviet experimental radio astronomy. At that time, he was the head of a group in the Oscillation Laboratory of FIAN, and was working on studies of the physical properties of solid bodies and electrolytes using radio methods.

The experience acquired by Khaikin during the Second World War with the construction of radar systems helped him develop a method for observing the radio emission of the Sun during an eclipse.

The expedition began with an unpleasant surprise; a shelf of heavy ice with a width of 5 km formed in the usually unfrozen port of Liepaya from which the ship *Griboedov* (Fig. 1.4) was to set sail for Brazil. The icebreaker *Sibiryakov* was called from Riga, and was supposed to make a passage through the ice in order to lead the ship to clear water. After the war, there were many mines left in the port, and there was a real danger of getting blown up by one. The *Griboedov* arrived in Sweden only

[2]Izvestiya Akademii Nauki SSSR, Seriya fizika, 1948, 12, No. 1, p. 5.

Fig. 1.3 Semen Emmanuilovich Khaikin (1901–1968)

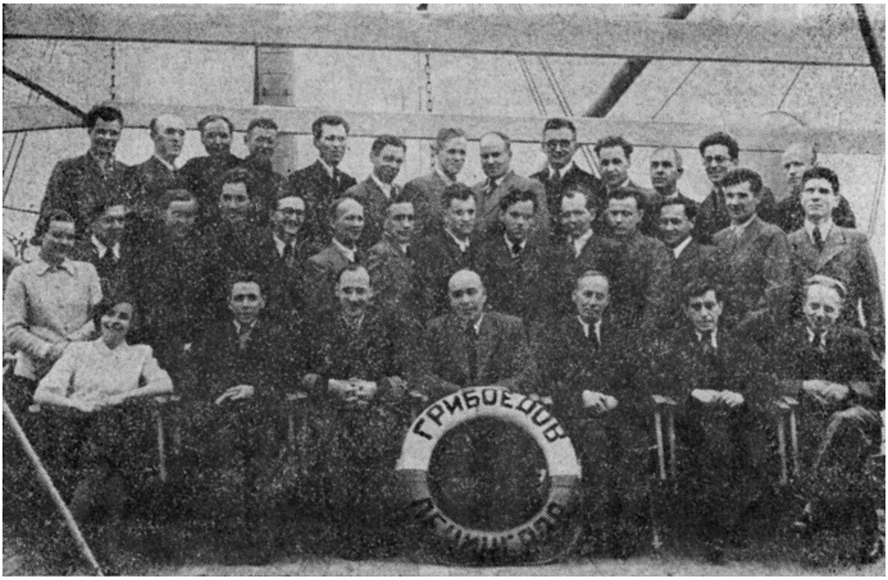

Fig. 1.4 Participants of the Brazilian expedition of the USSR Academy of Sciences on the desk of the "Griboedov". Included in the picture are the well known scientists and engineers S. E. Khaikin (*bottom row, first on the right*), G. A. Ushakov (*lower row, fourth from the right*), V. L. Ginzburg (*middle row, fourth from the left*), B. M. Chikhachev (*middle row, sixth from the right*), and I. S. Shklovskii (*upper row, second from the right*)

on April 15, where it underwent demagnetisation over the course of two days. The ship arrived at the Brazilian port of Salvador on May 10, 1947, only ten days before the eclipse. The optical and ionospheric groups set out by train to the city of Arasha.

There was now little time to set up and test the equipment. In spite of its characteristics, which were quite good for that time, the radar station was not usable for