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RADIOASTRONOMICAL INVESTIGATIONS IN THE MILLIMETER AND SUBMILLIMETER BANDS

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I. INTRODUCTION

RECENT progress in radioastronomy in the millimeter band (observation of a number of discrete radio-emission sources with unusual spectra, discovery of the variability of radiation of certain sources at millimeter wavelength, etc.) have stimulated interest in these investigations and served as a powerful impetus for further development of this research. At the present time new instruments, equipped with modern technical devices, are being installed in many of the world's observatories, and balloon and satellite experiments are being organized. The development of radioastronomical in the millimeter and submillimeter bands will be accelerated by the fact that these bands are now regarded as promising for communication in outer space, and also for communication between the earth and outer space.

A number of theoretical considerations suggest that radioastronomical research in the millimeter and submillimeter bands is highly promising. Just these spectral regions contain the most intense rotational bands of the gases making up the planetary atmospheres and having the greatest abundance in the interstellar medium. The line strengths are larger by several orders of magnitude in the millimeter and submillimeter bands than in the centimeter band. The phenomena of dielectronic recombination in the atmospheres of stars and in hot nebulas lead to the occurrence of lines that apparently lie in the millimeter band. Solar observations at the millimeter and submillimeter wavelengths are the most effective means of investigating the sun's lower chromosphere. Finally, the maximum of the spectrum of the relict cosmic radiation lies apparently in the millimeter band.

Investigations in the millimeter ($\lambda = 1-10$ mm) and submillimeter ($\lambda = 50-100\ \mu$) bands occupy a special place in radioastronomy both with respect to the technique and from the methodological point of view. At these wavelengths, the disturbing action of the earth's atmosphere is particularly strong, and difficulties in producing sufficiently sensitive radiotelescopes become most acute.

The purpose of the present review is to describe the present status and to some degree also the nearest future of this promising field of radioastronomy. Intense absorption of millimeter and especially submillimeter radio waves by the earth's atmosphere makes it necessary to take the instruments outside the atmosphere with the aid of balloons, rockets, and artificial satellites. The experimental technique of such investigations, as well as of problems solved with its aid, have been considered in [1]. Principal attention is paid in this article to an analysis of the possibilities of land-based instruments with the aid of which most of the radioastronomical observations at 0.7–10 mm were performed. These possibilities are far from exhausted.

A number of problems concerning experimental techniques in the submillimeter band is discussed in detail in the review[2], to which we shall refer the reader when necessary. We shall also take into account here the fact that many experimental data on radioastronomical investigations in the millimeter band, as well as their interpretation, are discussed in several recently published monographs.[3–7]

II. RADIOTELESCOPES: ANTENNAS AND RECEIVING APPARATUS

1. Antennas

At millimeter and submillimeter wavelengths one uses in radioastronomy for the most part mirror antennas, with the aid of which it is possible to obtain an effective area sufficient for the reception of radio emission from discrete sources and planets. In the investigations of atmospheric and distributed cosmic radio emission, horn and horn-lens antennas are sometimes used.[3, 9]

The construction of sufficiently large mirror antennas for the millimeter and submillimeter bands entails considerable technical difficulties. These difficulties are due primarily to the stringent requirements with respect to their surface accuracy. A parabolic antenna with a mean-squared deviation σ of the surface from ideal has a gain $G_0 \exp \sigma^2 (\sigma/\lambda)^2$,[10] where G_0 is the gain of an "exact" antenna, and λ is the working wavelength (this relation is valid if the correlation radius of the inhomogeneities is large compared with λ). If a gain loss of $0.1G_0$ is regarded as permissible, then this condition yields $\sigma \lesssim \lambda/30$. The deformation of the antenna during its rotation, during changes of the thermal conditions, or under wind loading should likewise not exceed this limit. Obviously, to maintain an exact surface is a more complicated problem than to construct an antenna with the required accuracy. The structure of a large antenna for the millimeter band should be sufficiently rigid, and measures must be taken to eliminate or cancel out thermal deformations. Good results are obtained by using antennas with a surface that can be regulated during the course of construction. A design of such an antenna (RT-22) was proposed in [11], where a method is described for constructing the exact surface by arranging its elements with the aid of a knife-edge pattern, and where a principle was proposed and realized for a four-bearing suspension, contributing to a decrease in the weight deformation of the antenna.

Table I. Parameters of antennas for the millimeter and submillimeter bands

Organization	Diameter, m*	λ, mm	Surface-utilization coefficient, %	γ Gain, db	Directivity pattern, ang. min.	Aiming accuracy, ang. sec.	Relative precision of antenna construction	Remarks, literature
Crimean Astrophysical Observatory, USSR Academy of Sciences	22	2 8	7 40		1,2 1,6	20	$7\cdot10^4$	[18]; with incomplete irradiation of the mirror [14]
Physics Institute, USSR Academy of Sciences	22	4 8	7 40		1,6		$3,45\times10^4$	18 13
National Radio Astronomical Observatory, USA	11	1,2 3	20 40		0,70 1,2	5	10^5	45 15
То же	42	9,5	15		1,2	10	$4,6\times10^4$	15
Naval Research Laboratory, USA	26	9,55	25		1,6±0,1	30	$5\cdot10^4$	51, 60
Radio Observatory in Algonquin, Canada	46	8,6	5,5±0,5		1±0,1	30	$4,6\times10^4$	44
Lincoln Laboratory, USA	8,6	8,5	55±5	67,5	4,3±0,1	90		34, 35
BBC Cambridge Research Laboratory	9	8,6		66,4±0,4	4,6±0,2			38, 55, 59
University of California	6	12,65			8,5	60		57
University of Texas	4,9	3,2	54	67,8	3,5	38	$7,7\times10^4$	22, 39, 49
Aerospace Corporation, USA	4,6	3,3			2,8	20	$6\cdot10^4$	23, 40
Queen Mary College, England	4,5						$3,5\times10^4$	21
Radiophysics Institute of the Gor'kii University, USSR	4,0	3,9	30		4,6±0,1	60	10^4	58
Naval Research Laboratory, USA	3	8,6	60		12,6			50
University of California	3	8,35		$5\cdot10^5$	10,3			36, 37
Main Astronomical Observatory, USSR Academy of Sciences	100×3	8	28		0,25×12		10^5	[30], immobile variable-profile-antenna radio telescope
Radiophysics Institute of the Gor'kii University, USSR	25×2	2	40±5		0,33×5	10	$1,2\times10^5$	[31]; immobile radio telescope

*There is reference in the literature to two millimeter-band antennas with 8.5 and 9 m diameter [56], but there are no detailed data on their parameters.

These principles were further developed in [12].

On the basis of these developments, the two largest domestic antennas for the millimeter band were constructed, namely RTT-2 of the Oka Radio Astronomical Station of the P. N. Lebedev Physics Institute of the U.S.S.R. Academy of Sciences[13] and RT-22 of the Simeiz Branch of the Crimean Astronomical Observatory of the U.S.S.R. Academy of Sciences.[14] Data on these antenna are given in Table I. A picture of RT-22 of the Crimean Observatory is shown in Fig. 1. Instruments of the RT-22 type have the largest effective area and the largest resolution of all the antennas designed to operate at a wavelength λ = 0.8–1 cm (Table I). The limiting resolution of RT-22 is apparently about 1′.

FIG. 1. Radiotelescope RT-22 of the Crimean Astrophysical Observatory of the USSR Academy of Sciences [13].

This is approximately the same order as the resolution of the largest antennas for the centimeter band. Further increase of the resolution of wave-rotating antennas entails apparently the need for shielding the radiotelescopes against uneven solar heating and wind loads with the aid of pavilions analogous to the towers of optical telescopes.* This is precisely the procedure used by the designers of the 11-meter telescope of the National Radioastronomical Observatory in the U.S.A.[15] (Fig. 2). It was expected that the minimal working wavelength of this antenna would be about 1 mm, and consequently the resolution expected was about 20″, but these have so far not been realized. Nevertheless, this antenna is apparently the "largest" (with respect to the effective area) full-revolution instrument operating at the short millimeter wavelengths (see Table I). The RT-22 antenna of the Oka Radioastronomical Observatory operated at a wavelength $\lambda = 4$ mm,[16] and the RT-22 of the Crimean Observatory even at $\lambda = 2$ mm,[18] but the coefficients of surface utilization at these wavelengths are quite low (see Table I) and the effective area is smaller than that of the 11-meter radio telescope at $\lambda = 3$ mm.

All other full-rotation radiotelescopes for the millimeter band have a much lower effective area than the three instruments referred to above. Most of them are in the U.S.A. (see Table I). A number of rather large radiotelescopes for the centimeter band (for example, the standard telescopes of 26 m diameter, constructed in the U.S.A.[19, 20]) can be effectively used at wavelengths $\lambda = 0.8-1$ cm. However, the operation of these instruments entails considerable difficulties, since their effective area depends significantly on their angular orientation, and also on their illumination by the sun.

The number of full-rotation telescopes suitable for operation in the submillimeter band is still small. In estimating the effectiveness of instruments for the submillimeter band it is necessary to take into consideration not only the precision with which the antenna is constructed, but also its location. The three rather large (diameter D = 4.5–4.9 m) paraboloids are suitable from the point of view of their quality for operation at $\lambda \sim 1$ mm[21-23] (see Table I), but all are located at sufficiently low altitudes above sea level. As indicated in the next chapter, in observations at wavelengths 0.5–0.3 mm the height of the instrument above sea level should be not less than 3.5–4 km. At the present time, insofar as we know, there is still no submillimeter radiotelescope at such an altitude. In the U.S.A. it is planned to construct a parabolic antenna of 4–5 m diameter, suitable for operation at $\lambda = 0.3$ mm; the antenna should be installed in the mountains of Peru at an altitude of about 4 km above sea level.

*When large instruments are constructed for the centimeter band [17], it is convenient to place them in a radio-transparent pavilion.

FIG. 2. Radiotelescope with 1-m diameter antenna of the National Radioastronomical Observatory of the USA [15].

At short millimeter wavelengths, optical telescopes are also used successfully. The greater part of the observations of planets and discrete sources at 1.2 mm, performed in the U.S.A.,[24] were obtained with the aid of the Mount Palomar telescope of 5 m diameter. The construction of an optical instrument twice as large is also now planned in the U.S.A.[25]

From the information concerning millimeter-band radiotelescopes listed in Table I, it is clear that they are not inferior in resolving power to the largest centimeter-band radiotelescopes. This is perfectly natural since the factor D/λ, which determines the resolving power, is rigidly connected with the ratio D/σ characterizing the difficulty of constructing a radiotelescope. The best antennas for centimeter wavelengths have ratios $D/\sigma = (3-6) \times 10^4$.[26] This parameter is of the same order of magnitude also for the antennas in the millimeter band (see Table I).

However, the effective areas of radiotelescopes operating at millimeter wavelengths are much smaller than those of long-wave instruments. Therefore the possibilities of radioastronomical investigations of ob-

FIG. 3. Meridian radiotelescope of the Radio Physics Institute at the Gor'kii University (RT-25 × 2)[31].

jects whose spectral index is $\alpha \lesssim 0$ in the millimeter band are much more modest than at centimeter or decimeter wavelengths.

The development of a large sufficiently accurate radiotelescope becomes much simpler if it is made immobile in at least one of its coordinates. This is the easiest way of obtaining large effective areas. There is a large number of known antenna systems such as the variable-profile antenna (APP) of the Main Astronomical Observatory of the U.S.S.R. in Pulkovo,[27] the Kraus system (University of Illinois[28]), and the antenna in Nancy (France),[29] which are successfully used for regular astronomical observations at centimeter and decimeter wavelengths. Of these, the variable-profile antenna is the most accurate. In 1967, it was modernized, as a result of which it was possible to employ the variable profile antenna at 8 mm. The attained resolving power in direct ascension was 15″.[30] In principle, the variable profile antenna admits of adjustment in a certain interval of azimuthal angles, but at millimeter wavelengths it was used as a meridian instrument.[30]

The second transit-type radiotelescopes for millimeter wavelengths was also constructed in the U.S.S.R. (the "Zimenki" Radioastronomical Observatory of the Radiophysics Institute of the Gor'kii University).[31] The construction is similar to that of the Kraus radiotelescope.[28] Antenna systems of this type have many advantages over variable-profile antennas.[31, 43] The dimensions of the Zimenko radiotelescope are 25 × 2 m. A picture of RT-25 × 2 is shown in Fig. 3, and its parameters are listed in Table I. RT-25 × 2 was successfully tested at 2.2 and 4.1 mm. Thus, transit-type instruments have the maximum resolving power (with respect to one of the coordinates) in the millimeter band. The parameter D/λ for these telescopes* (here D is the largest antenna dimension) is of the order of 10^5 and more. Further development of meridian instruments will make it possible to attain considerable progress also in the effective area of the radiotelescopes for the millimeter and submillimeter bands.

With the aid of transit-type radiotelescopes it is possible to solve successfully such radioastronomical problems as scanning of the sky, measurement of positions and dimensions of sources, investigations of the distribution of the radio brightness of discrete radio sources and planets, observations of phase effects of planets, and investigations of the variability of radio emission from discrete sources. Certain problems of solar radioastronomy can also be solved with meridian instruments. On the other hand, problems connected with the need for tracking an investigated object for a long time, for example investigations of short-period variations of the intensity of radio emission of sources, observation of occultations, investigations of the monochromatic radiation of the galaxy and spectroscopy of planetary atmospheres, radar investigations, mapping of the sun and the moon, study of solar activity (especially flares), etc., can be effectively solved only with the aid of full-rotation telescopes.

Thus, both at present and in the nearest future, the main instruments for radioastronomical investigations in the millimeter and submillimeter bands should be total-rotation radiotelescopes with mirror antennas. The possibilities of using interferometers and aperture synthesis at these wavelengths are not yet sufficiently clear. It is obvious for the time being that the construction of an interferometer for the millimeter bands entails considerable difficulties of both technical nature (the problem of channeling the energy, the development of a stable heterodyne, etc.) and fundamental difficulties (the presence of atmospheric inhomogeneities, which become manifest particularly strongly manifest at millimeter and submillimeter wavelengths). Nonetheless, the use of many-element antenna systems makes it possible to increase both the effective area and the resolving power of the radiotelescope. This tendency becomes very clearly manifest in the classical bands of radioastronomy, the centimeter and the decimeter bands.[33, 42]

A two-antenna interferometer for the millimeter band is under construction in our country (the design was developed by the N. É. Bauman Moscow Higher Technical School jointly with the P. N. Lebedev Physics Institute of the U.S.S.R. Academy of Sciences[47]). Each of the antennas of the interferometer, of 7.5 m diameter, will be constructed with accuracy ±0.1 mm. It is expected that the interferometer, the base of which is 250 m, will operate it in the wavelength range 1–8 mm used to investigate the distribution of the brightness over the moon, the sun, planets, and discrete radio-emission sources. It is also planned to solve certain problems in radar astronomy.

Considerable progress in the development of instruments for the millimeter and submillimeter bands will be reached apparently when the problem of constructing orbiting radiotelescopes and lunar observatories is solved. The design of a 30-meter orbiting telescope operating at ~1 mm is regarded to be perfectly realistic.[48]

We do not consider in this paper problems involved in the design and technology of antennas for the millimeter band and systems for their irradiation. The reviews[10, 45] contain information concerning these questions, and also concerning the necessary precision with which reflecting antennas are to be constructed. Developments of immobile multisection antennas, the investigation of the dependence of their efficiency on different factors are the subjects of [42, 46] Information on the designs of antenna-feeder systems can be found in [32].

In conclusion we note that many problems in radioastronomical research (measurement of integral radio-emission fluxes from the sun, the moon, and some of the most intense discrete sources, observation of the distribution of cosmic radio emission) can be successfully solved with the aid of relatively small instruments (see, for example [52–54]) having antennas of approximately 1 meter diameter.

2. Radiometers for the Millimeter and Submillimeter Bands

At these wavelengths, the most widely used is the modulation radiometer. Null and correlation schemes are hardly ever used. This is due to the distinguishing features of the millimeter and submillimeter bands. As is well known,[61] a null system makes it possible to attain a larger sensitivity then a modulation system, but the fluctuations of the parameters of the radiometer lead to the appearance of the so-called "anomalous" noise with a spectrum in the form $F^{-\beta}$, which affects adversely the sensitivity of a null-type radiometer. By using the modulation scheme of reception it is possible, at sufficiently high modulation frequency, to make the influence of the "anomalous" noise barely noticeable. In the millimeter band one uses in radiometers broadband intermediate-frequency amplifiers (with bandwidth $\Delta f \sim 1$ GHz). When the bandwidth of the intermediate-frequency amplifiers is increased, the requirements with respect to the stability of its gain become more stringent. At $\Delta f = 1$ GHz and at a radiometer output time constant $\tau_{out} = 1$ sec, the relative stability of the gain during a time on the order of τ_{out} should be not worse than 3×10^{-5}. In order to eliminate completely the influence of the "anomalous" noise, it is necessary to increase the modulation frequency in broadband radiometers.[62] As to the correlation scheme, the rigid requirements[63] concerning the identity of the phase and frequency characteristics of the amplifiers employed in them are also difficult to meet in broadband radiometers.

The millimeter and submillimeter bands are adjacent both to the optical band (to infrared waves) and to the microwave band, so that both IR and radio reception methods are applicable. This means the use of incoherent receivers, the output effect of which is proportional to the energy of the received signal (their action is analogous to the action of thermal receivers) and linear (superheterodyne or direct amplification) receivers.

The nonlinear elements used in incoherent receivers are bolometers,[64] InSb and GaAs photoresistors,[65] Golay cells,[66] evacuated baretters,[79] and point-contact diodes.[67, 68] The operation of these receivers in the millimeter and submillimeter bands was considered in sufficient detail in recent reviews,[2, 69, 70] and we shall pay similar attention here to a comparison of these devices with receivers of other types, and also to the possibilities of their improvement.

Reception of millimeter and submillimeter radiation by microwave methods is made difficult by the insufficient efficiency of the existing amplifiers at such short wavelengths. Only in the long-wave part of the millimeter band is it possible to start to use lasers,[71, 72] parametric amplifiers,[73, 74] and traveling-wave tubes tubes.[75] These devices are successfully used also in radioastronomy (see, for example,[74–76]). Analogous amplifiers for wavelengths $\lambda < 8$ mm are apparently still in the development stage.[77–80] The main type of receiver is the superheterodyne with a mixer at the input. In the development of such a receiver for the millimeter and submillimeter bands, the following difficulties arise: 1) the appreciable attenuation of the radio waves in the millimeter band on passing through different elements of the waveguide channel (rectifiers, circulators, bridges, etc.); 2) the absence of pairs of mixing diodes with identical parameters at the high and intermediate frequencies; 3) large intrinsic noise of the generators used as heterodynes. The first cause makes it necessary to search for a simpler functional radiometer circuit, in which the number of different tuning elements is reduced to a minimum. In addition, it is impossible to make the input channel long enough. As is well known[81, 82], an increase of the length of the signal channel is necessary to attenuate the interference between the intrinsic noise of the radiometer, which leads to the occurrence of intense false signals. The use of different quasioptical elements in the high-frequency channels of the radiometers is apparently quite promising (for example, oversized waveguides, the attenuation of which is much smaller than in the waveguides of the main section).

The absence of pairs of mixing detectors and the large intrinsic heterodyne noise lead to the need for using single-ended mixers with ultrahigh intermediate frequencies.[83] This makes it possible also to increase the bandwidth at the intermediate frequencies and to increase the sensitivity of the radiometer. The effectiveness of this method was demonstrated in [84] and, independently but somewhat later, in [85]. Figure 4 shows a picture of the high-frequency block of a broadband receiver for 3.7–5.7 mm, described in [85] and used for observations of Jupiter and 3C144.[58] Radiometers with broadband intermediate frequency amplifiers, operating in the submillimeter band, have by now been constructed.[86]

This raises the question of the preferable reception method in each particular case. The answer can be obtained only when the concrete problem to be solved with the aid of the radiometer is considered.

Cosmic radio emission in the millimeter and submillimeter bands has a continuous spectrum and is usually weakly polarized. In observing absorption lines of interstellar matter or gases making up the atmosphere of planets and stars, it is necessary to deal with quasi-monochromatic signals. Finally, radar investigations entail the reception of coherent polarized signals. The main criterion in all cases is the sensitivity of the receiver. To receive radio emission with a continuous spectrum it is important to have sensitivity with respect to the spectral density of the signal. In measurements of quasisinusoidal signals, power sensitivity is important. We therefore present below a comparison of receivers for the millimeter and submillimeter bands with respect to their sensitivity to signals with a continuous spectrum (ΔT—minimum observable increment of the effective input temperature), and also with respect to sensitivity to sinusoidal signals (ΔP—minimal observable increment of the power of a sinusoidal signal).

The most sensitive indicators of signals with continuous spectra in the short-wave regions of the milli-

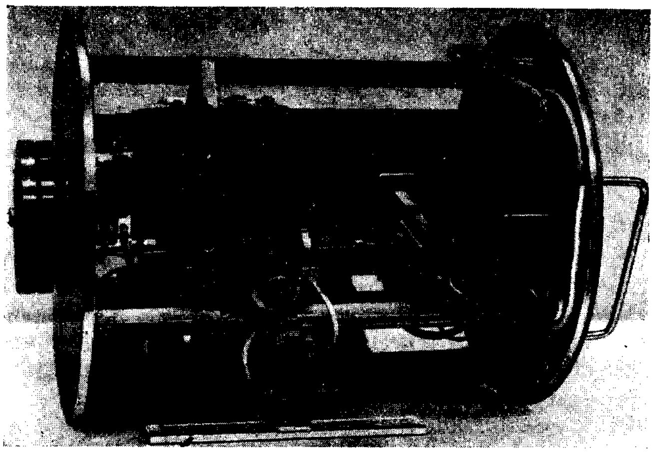

FIG. 4. High frequency block of radiometer for the 3.7–5.7 mm band. It is installed in the focus of the four-meter radiotelescope of the Radio Physics Institute at the Gor'kiĭ University [58].

meter* and submillimeter bands are incoherent receivers with germanium bolometers cooled to the temperature of boiling helium.[64, 87] Somewhat inferior in sensitivity are receivers using indium antimonide (the so-called "hot electron" effect), also cooled to helium temperatures.[69, 70, 88–90] The parameters of both receivers are listed in Table II. The high sensitivity of incoherent receivers is, to a considerable degree, the result of the fact that they are broadband. In many cases this quality of the instrument is undesirable, especially in land-based observations, when it is necessary to take into account the atmospheric absorption of the radio waves. The bandwidth of the radiometer should be sufficiently small compared with the width of the "transparency window" of the atmosphere. In particular, it seems to us that the bandwidth of the receiver of F. Low, used in radioastronomical observations[91–92] (35% of the central part of 250 GHz) is too large, since it does not satisfy this requirement. The advantage of thermal receivers in measurements of signals with a continuous spectrum can apparently be realized more fully in observations outside the atmosphere.

To observe telluric rotational lines, and also lines produced in the atmospheres of other planets, a frequency resolution of the order of a fraction of 1 GHz may be sufficient.[93–96] Incoherent receivers at such a bandwidth are frequently of lower sensitivity than radiometers with superheterodyne receivers (see Table II). Observations of rotational lines of interstellar matter call for a much larger frequency resolution, on the order of dozens and hundreds of kHz. The sensitivity of incoherent receivers is proportional to the bandwidth of the received frequencies Δf. The radiometers with linear receivers do not lose their sensitivity so rapidly with decreasing Δf, in proportion to $(\Delta f)^{1/2}$. Table II gives data on the sensitivity of the radiometers and $\Delta f = 10^5$ Hz. Outstanding among all the receivers used in the short-wave part of the millimeter band is the superheterodyne with indium antimonide* cooled to helium temperature.[97–99] Inasmuch as this receiver is based on volume effects not subject to the frequency limitations applicable to point-contact semiconducting diodes, it is an unusually convenient instrument for spectral investigations in the submillimeter band. The inertia of the volume effects in InSb does not make it possible to use it for frequency conversion with the aid of an ultrahigh intermediate frequency and to employ a sufficiently broadband intermediate frequency amplifier, so that the sensitivity of broadband radiometers with mixers based on point-contact diodes in the millimeter band is somewhat higher than that of the receiver described in [99].

Table II gives also data on the sensitivity of receivers of various types with respect to the power of the sinusoidal signal at an output bandwidth of 1 Hz. This information is useful for the selection of the optimal receiver in planetary radars. As seen from this list, the InSb superheterodyne is inferior in sensitivity only to masers and parametric amplifiers of the 8-mm band.

The tendency to extend the use of masers and other amplifiers to shorter wavelengths will apparently become stronger. In any case, masers are not subject in principle to any frequency limitations in the millimeter and submillimeter bands.[100] Improvement in the design of masers used at $\lambda = 8$ mm will make it possible to attain a sensitivity on the order of $\Delta T = 10^{-2}$ °K.[71, 100] Comparable values will be apparently obtained also with masers operating at shorter wavelengths. Therefore in the future the incoherent receivers will remain the most sensitive receivers for signals with uniform continuous spectra, since their progress will make it possible to attain $\Delta T \sim 10^{-3}$ °K.[64]

Very highly promising are investigations of various low-inertia volume effects (the Josephson effect,[101–103] cyclotron resonance in semiconductors,[104–105] nonlinearity connected with the dependence of the effective mass of the electrons on the quasimomentum,[106] etc.), the use of which apparently makes it possible to increase greatly the sensitivity of broadband superheterodyne radiometers. Table III characterizes to some degree the expected values of ΔT and ΔP, which can be obtained in the nearest future.

Other ways of increasing the sensitivity of radiometers at millimeter and submillimeter wavelengths would be the development of cooled parametric amplifiers,[70] the use of new semiconducting materials in mixers and in video diodes,[107] and the development of cooled mixers in conjunction with parametric amplifiers as intermediate frequency amplifiers.[85] The capabilities of such devices are also assessed in Table III.

It is not excluded that an important role in radioastronomy will be played also by gas amplifiers,[108] which can be successfully used even now as preamplifiers in radars and in communication systems.

It should be noted that in the millimeter and submillimeter bands it is necessary to deal with quantum effects, and therefore some of them (for example, photon noise) can greatly limit the sensitivity of the receiving systems. Questions involving the influence of quantum effects on the sensitivity of radiometers are considered in detail in [119].

Radio waves in the millimeter and submillimeter bands are intensely absorbed by the atmosphere. Therefore its thermal radio emission is quite large. Radio

*The long-wave part of the millimeter band, as already mentioned above, is sufficiently well accessible, for it is possible to use there masers and parametric amplifiers.

*Receivers of this type have so far not been used in radioastronomy.

Table II. Information on the sensitivity of radio astronomical receivers

Type of receiver	λ, mm	Working temperature, °K	Δf, GHz	ΔT, °K	ΔT′, °K	ΔT″, °K	ΔP, W	Remarks, literature
Germanium bolometer	1.2	2.15	87.5	0.05	4.1	—	$4\cdot10^{-14}$	64 ΔT′ designed for Δf = 1 GHz
	2	2.15		7.2	7.2	—	10^{-13}	66 $\Delta f = 10^{-4}$ GHz
Антимонид индия	0.7—1.8	4	260	0.03	7.8	—	10^{-13}	120 The dash in the column for ΔT″ denotes Δt″ > 10^4 °K
	0.4—1.2	4	550	0.05	27.5	—	—	88
	0.5	1.5		—	72	—	10^{-12}	66
	2	1.5	15	4.8	70	—	10^{-12}	66
	4	1.5	—	—	7.2	—	10^{-13}	99
Superconducting film bolometer	2	3.7	—	—	220	—	$3\cdot10^{-12}$	66
Cyclotron resonance in germanium	8	4	—	—	145	—	$2\cdot10^{-12}$	66
Point-contact diode	0.48	300	120	15—25	1.8×10^3	—	$3—4\times10^{-11}$	68
	0.74	300	60	20	1.2×10^3	—	$2\cdot10^{-11}$	68
	0.87	300	35	20	700	—	10^{-11}	68
	1.26	300	30	10—15	300	—	$(0.5—1)\times10^{-11}$	68
	1.45	300	25	10—15	250	—	$3.7\cdot10^{-12}$	68
	2.0	300	15	120	1.8×10^3	—	$2.5\cdot10^{-11}$	79
Carbon bolometer	2	1.5	15	48.0	720	—	$4.5\cdot10^{-11}$	79
Vacuum baretter	2	300	15	190	2.8×10^3	—	$4.5\cdot10^{-11}$	79
Optical-acoustical receiver	5	300	50	43	2.1×10^3	—	$3.7\cdot10^{-11}$	66
Superheterodyne	0.5	300	1.6	16	20	$2\cdot10^3$	$1.1\cdot10^{-17}$	8, 86 Sensitivity ΔT in the radiometer regime: the direct and reflected channels are received. The value of ΔP is calculated for a linear receiver with Δf = 1 Hz
	0.95	300	2	10	14	1.4×10^3	$8\cdot10^{-18}$	121
	1.8—2.7	300	0,6	1.5	1.15	115	$6.5\cdot10^{-19}$	85
	2.15	300	0,03	8,3	1.4	140	$8\cdot10^{-19}$	79
	2.15	300	1.5	0.9	1,1	110	$6.2\cdot10^{-19}$	84
	3.2	300	0,01	7	0.7	70	$4\cdot10^{-19}$	122
	3.3	300	2	0.3	0,42	42	$2.4\cdot10^{-19}$	114
	3.7—5.7	300	0,6	0.7	0.54	54	$3\cdot10^{-19}$	85
	4,3	300	0.1	0.6	0.19	19	$1.0\cdot10^{-19}$	123
	4,3	300	0.1	1.5	0.47	47	$2.6\cdot10^{-19}$	79
	4.3	300	0.06	5	0.38	38	$2\cdot10^{-19}$	124
	8	300	1.0	0,4	0.4	40	$1.1\cdot10^{-19}$	125
	9.55	300	0.01	0.8	0.08	8	$4.4\cdot10^{-20}$	60
	10.0	300	0.01	0.8	0.08	8	То же	116
Superheterodyne using InSb	4	1.5	—	—	—	1.4	$8\cdot10^{-21}$	99
Maser	3—4	—	0,4	0,15	—	9,5	$5.5\cdot10^{-20}$	79
	8	1.7	0.05	0.2	—	4.5	$1.2\cdot10^{-20}$	71
	8	4.2	0.02	0.09	—	1,10	$3\cdot10^{-21}$	76
Parametric amplifier	8	300	0.3	0.06	—	3.3	$6.2\cdot10^{-21}$	73 Direct amplification radiometer
	8—12	300	0,6	0.027	—	2.1	$4\cdot10^{-21}$	74
Gas amplifier	1,16	300	7.6×10^{-3}	0.9	—	8	$2.2\cdot10^{-20}$	108
Traveling-wave tube WJ-224	4	300	30	0.4	2.2	220	$6\cdot10^{-19}$	79

Table III. Expected sensitivity of receivers in the millimeter and submillimeter bands

Type of receiver	ΔT, °K	ΔP, W
Germanium bolometer	10^{-3}	$5\cdot10^{-15}$
Superheterodyne with mixer based on a low-inertia volume effect	10^{-2}	10^{-20}
Maser	10^{-2}	10^{-21}
Cooled parametric amplifier	10^{-2}	10^{-21}
Gas amplifier	0,1	10^{-20}
Broadband superheterodyne with cooled mixer based on a point-contact diode.	0,1	10^{-19}

emission of the atmosphere is subject to highly irregular oscillations, which lead to the appearance of excess noise at the output of the radiometer. Fluctuations of thermal emission of the atmosphere* were considered in [110, 111], and their influence on the sensitivity of radioastronomical receivers was analyzed in [112, 113] This influence can be greatly reduced by scanning the directivity pattern of the radiotelescope antenna.[113, 114] Scanning, however, is not always realizable (for technical reasons). In [115] is considered the question of optimal regime of observation in the case when the radiometer output contains nonstationary fluctuations similar in their spectrum to the fluctuations of the radio emission of the atmosphere.

We have not considered here in detail the functional schemes of radiometers used in radioastronomy at millimeter and submillimeter wavelengths. In general they are similar to those used at longer wavelengths. In investigations of quasimonochromatic signals, use is also made of frequency modulation and multichannel radiometers.[116] The arrangement of a polarimeter for 8 mm wavelength[117] is similar to that of polarimeters for the centimeter band. It should be noted that polarization measurements were carried out so far only at λ = 8 mm (observations of the sun[118, 205] and of the moon[238]) and at λ = 9.55 mm (observations of several discrete sources[119]).

III. RADIOASTRONOMICAL MEASUREMENT PROCEDURE IN THE MILLIMETER AND SUBMILLIMETER BANDS

Even if the atmospheric absorption is sufficiently small to be able to receive reliably the radio emission of some extraterrestrial object, exact measurements of the intensity of this radio emission are made exceedingly difficult by the uncertainty of the optical thickness of the atmosphere. The optimum method of measurement is a comparison of the investigated object with another extraterrestrial source, the emission of which is well known. But such a possibility may not arise. In addition, a comparison of different objects must be made with allowance for the difference between their positions in the celestial sphere, and to this end it is necessary also to know the absorption by the atmosphere and the degree of its homogeneity.

We present below brief information on atmospheric absorption of radio waves in the millimeter and submillimeter bands, and consider certain methods of measuring cosmic radio emission at these wavelengths.

1. Absorption of Millimeter and Submillimeter Radio Waves by the Earth's Atmosphere

Millimeter and submillimeter waves are strongly absorbed by clouds and rain,[127] and therefore radioastronomical observations at these wavelengths are practically impossible in cloudy weather. In an atmosphere free of hydrometeors, the major role in the absorption of radio waves is played by water vapor and by oxygen. The coefficients of molecular absorption of radio waves in H_2O and O_2 were calculated in the entire wavelength band of interest to us.[128] As shown in the reviews,[128, 129] calculations of the absorption coefficients for wavelengths corresponding to resonant lines are in very good agreement with experiment. Far from resonance and in the intervals between the resonances (in the so-called "transparency windows" of the atmosphere, which are of greatest interest for radio astronomy), certain discrepancies between theory and experiment are observed. The measured coefficient of absorption of radio waves in H_2O is usually 1.5–2 times larger than that calculated. The reason for this discrepancy is not yet clear. As to oxygen, the correctness of the calculations of the resonant and nonresonant absorption in O_2 is sufficiently well confirmed by experiment.[130, 96]

Cosmic radio emission travels to the antenna through the entire layer of atmosphere if the observer is located on the earth, so that it is necessary to know the total absorption along the line of sight. It is customary to use a plane-stratified model of the atmosphere (this model is correct at zenith angles $\theta \lesssim 85°$ [131]), and it is assumed that the total absorption on the line of sight is $\gamma = \Gamma \sec\theta$, where Γ is the optical thickness of the atmosphere at the zenith, $\Gamma = \kappa_W H_W + \kappa_O H_O$, where κ_W and κ_O are the radio wave absorption coefficients in H_2O and O_2 at sea level, and H_W and H_O are the effective path lengths of water vapor and oxygen. Thus, besides the absorption coefficient, it is necessary also to know the effective path length.

It can be assumed with high accuracy (for waves corresponding to the "transparency windows" of the atmosphere) that $\kappa_W(h) = \exp(-h/H_W)$, where h is the altitude above sea level. This is demonstrated in [132, 133]. The value of H_W depends little on the air temperature and altitude above sea level;[133] H_W changes from winter to summer in the range 1.48–1.56 km. An ex-

*The question of these fluctuations is considered in greater detail in Ch. III.

perimental determination of the effective path length of water vapor at millimeter wavelength[96, 134, 135] showed agreement with the calculations.

The effective path length of atmospheric oxygen, shown in [133], depends essentially on the altitude above sea level and on the air temperature. If $h \lesssim 5$ km, it can be assumed that the optical thickness of the oxygen in the atmosphere depends approximately exponentially on the altitude. But the argument of the exponential does not coincide with the value of H_O (the optical thickness decreases somewhat more rapidly with increasing h than the quantity κ_O). This circumstance is particularly important for the determination of H_O from the results of radioastronomical measurements of the function $\Gamma(h)$.[133]

At sea level $H_O = 0.86\,[(T_a/40) - 1]$, where T_a is the air temperature in the layer next to the earth. Calculations of the effective length of the oxygen path were also verified experimentally[96, 134] and found to agree with experiment. Using the results of the calculations of κ_W, κ_O,[128] H_W, and H_O,[133] it is possible to find the optical thickness of the atmosphere in any of the "transparency windows." Table IV lists information on the central wavelengths of these windows for the band 0.86 mm–40 μ and the absorption coefficients at these wavelengths for different altitudes above sea level (the calculation accuracy is ± 30–50%).

The optical thickness of the atmosphere in the "transparency windows" of the millimeter band (λ = 8, 3.4, 2.3, and 1.4 mm) has been sufficiently well investigated by radioastronomical methods in [96, 134, 135, 137]. The results of these investigations are discussed in detail and compared with theory in a recently published review,[129] and are therefore not presented here. We confine ourselves only to the remark that absorption of millimeter wavelengths is quite small and observations in the "windows" can be carried out even at sea level. The observation conditions are greatly improved at an altitude $h \sim 3$ km.

The data of Table IV can be used to estimate the efficacy of the operation of radiotelescopes at submillimeter wavelengths in landbased observations. Submillimeter wavelengths are so strongly absorbed by water vapor, that observations at sea level are possible in moderate latitudes only in the winter time. As shown by experiment,[136] at T_a = 50°C the amount of water vapor in the atmosphere is small enough to carry out land-based observations in the wavelength interval 200–300 μ. At $\lambda < 200\,\mu$, observations at sea level are practically impossible. The optical thickness of the atmosphere at the wavelengths at which the absorption is due to water vapor decreases rapidly with increasing h. In Table IV are given data on the transparency of the atmosphere in "windows" at h = 4 and 8 km. The transparency of the atmosphere in the winter at h = 4 km is sufficient for the performance of observations at wavelengths $\lambda \gtrsim 0.2$ mm. A radioastronomical observatory on high mountains can successfully operate in the winter at h = 8 km in all the "transparency windows" of the submillimeter band. It is then possible to solve such radioastronomy problems as observations of the sun, the moon, planets, and discrete sources, and measurements of the distributed cosmic radio emission. Spectral investigations may apparently be hindered by an abundance of telluric absorption lines, which so far have not yet been sufficiently well studied.

2. Radio Emission of the Atmosphere and Its Fluctuations

The atmosphere not only attenuates the cosmic radio emission, but produces its own thermal radiation, against the background of which the cosmic objects must be observed. The intensity of this background is as a rule so large that its random variations greatly limit the sensitivity of radiotelescopes.

The intensity I of thermal radio emission of the atmosphere can be obtained by integrating the radiation transport equation for an inhomogeneous isotropic medium.[3, 138] In the Rayleigh-Jeans approximation, we have $I = T_e(2k/\lambda^2)$, where T_e is the effective (or brightness) temperature and k is the Boltzmann constant. Since the air temperature amounts to 250–300°K, the Rayleigh-Jeans approximation is sufficiently accurate

Table IV. Optical thickness of the atmosphere in the millimeter and submillimeter bands. Only absorption in water was taken into account

λ, mm	Γ(nep) for ρ_0 = 7.5 g/m³, summer (290°K)			Γ(nep) for p_0 = 1 g/m³, winter (270°K)		
	h = 0	h = 4 km	h = 8 km	h = 0	h = 4 km	h = 8 km
0,86	3.1	0.217	0.015	0,48	0,034	0,0024
0.74	6.2	0.43	0,031	0,95	0,066	0,0048
0,65	17	1,19	0.085	0.62	0.183	0,013
0,45	18.6	1,3	0,093	2,86	0.2	0,014
0.36	22.2	1,55	0.111	3,42	0,24	0,017
0.34	32	2.24	0,16	4.92	0,34	0,025
0.32	41,4	2.9	0,207	6.38	0.45	0.032
0.29	98,2	6,9	0.49	15.1	1.06	0.075
0.22	108	7.6	0,54	16.6	1,16	0.083
0,2	93	6,5	0.46	14,3	1,0	0,071
0.164	370	25,9	1,85	57,0	4,0	0,28
0,152	176	12,3	0,88	27.1	1.9	0.135
0,12	340	23.8	1.7	52,4	3,66	0,26
0.037	207	14.5	1,03	32	2,24	0.16
0,07	320	22,4	1.6	49.4	3.45	0.247
0.061	216	15.1	1.08	33.2	2,32	0.166
0,054	207	14.5	1.03	31,8	2.22	0.159
0.046	196	13.7	0.98	30.6	2,14	0.153
0.042	93	6.5	0.46	14.3	1.0	0,071
0.038	83	5.8	0.41	12,8	0,9	0,064

at $\lambda \gtrsim 150\ \mu$ (i.e., in almost the entire submillimeter band). It is convenient to represent T_e in the form[139]

$$T_e = T_{av}(1 - e^{-\gamma}), \quad (1)$$

where T_{av} is a certain average temperature of the uniformly heated atmosphere, producing in the given direction θ the same radiation as the atmosphere with the real altitude temperature distribution. Using the plane-stratified model of the atmosphere and neglecting refraction phenomena, we obtain[139]

$$T_{av} = \left[\int_0^\infty \varkappa T(h) \exp\left(-\int_0^l \varkappa\, dl\right) dl\right] \Big/ \left[\int_0^\infty \varkappa \exp\left(-\int_0^l \varkappa\, dl\right) dl\right], \quad (2)$$

where κ is the total absorption coefficient and $dl = dh \cdot \sec\theta$. If $\kappa = \exp(h/H)$ and $T(h) = T_a - wh$, where w is the temperature gradient, then[52]

$$T_{av} = T_a - [wHS(\gamma)/(e^{\gamma} - 1)], \quad (3)$$

where $S(\gamma) \sum_{j=0}^{\infty} \frac{\gamma^j}{j - j!}$. Substituting (3) in (2), we obtain

$$T_e = T_a(1 - e^{-\gamma}) - wHS(\gamma)\, e^{-\gamma}. \quad (4)$$

In [133] we calculated the brightness temperature of the atmosphere with a more accurate approximation of the dependence of the temperature on the altitude: $T(h) = T_a[1 - qz/(1 + z^2)]$, where $z = h/h_0$ and q and h_0 are certain constants. Figure 5 shows plots of T_{av}/T_a against the optical thickness along the line of sight for those cases when the absorption of the radio waves in the atmosphere is determined by one of the gas components. In [54, 133] are considered also biexponential models of the absorbing atmosphere. Figure 5 shows also the ratio T_{av}/T_a determined from (3). A comparison of this curve with that calculated in [133] shows that the linear approximation of T(h) can be used, but calculations of the value of T_{av} at $h \gtrsim 8$ km by formula (3) can result in a large error.[133]

By applying the perturbation method to the transport equation, it is possible to obtain the fluctuations of the radio emission from an atmosphere[110, 112] that is free of hydrometeors. These fluctuations are due mainly to inhomogeneities of the temperature and humidity distribution in the air. As shown by calculations[110, 112] and by experiment,[140] the relative fluctuations of the brightness temperature of the atmosphere amount to

$$\delta T_e\ T_e = (0{,}2 - 1{,}0) \cdot 10^{-2} (\cos\theta)^{1/2}, \quad (5)$$

i.e., δT_e may be of the order of 1°K. Thus, the fluctuations of the radio emission of the atmosphere may limit the sensitivity of radiotelescopes.

Large antennas for the millimeter band have such a large D^2/λ ratio, that the absorbing and emitting layers of the atmosphere are effectively located in their Fresnel zone. The connection between the antenna temperature and the thermal radiation of the atmosphere is considered for this case in [141]

Atmospheric inhomogeneities average out over the aperture of the antenna,[112, 113] and this leads to a certain attenuation of the antenna temperature fluctuations. At equal areas, horizontally elongated apertures produce more effective averaging than round ones.[113] The antenna-temperature fluctuations connected with the

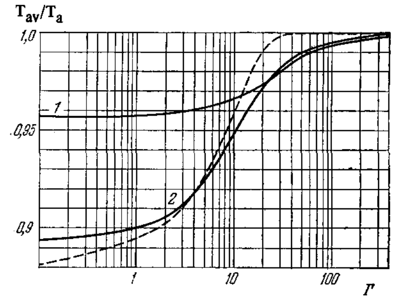

FIG. 5. Average temperature of the atmosphere as a function of the absorption along the line of sight. 1—Absorption in water vapor, 2— in oxygen. The dashed curve is a plot of formula (3)

motion of atmospheric inhomogeneities can be greatly attenuated (by approximately one order of magnitude) by scanning the directivity pattern of the radiotelescope.[113, 142] In the millimeter and submillimeter bands, however, the most radical method of combatting fluctuations of atmospheric origin is to mount the instrument at sufficiently high altitude above sea level.

The radio emission of the atmosphere (and also of the earth), received by the antenna of the radiotelescope, leads to an increase of the noise at the input of the radiometer. This increase is immaterial for radiometers customarily used at short millimeter wavelengths, since their effective noise temperatures are quite high (10^3–10^5 °K). At $\lambda \approx 8$ mm, masers are used in radioastronomy.[76] The sensitivity of radiotelescopes with masers depends significantly on the antenna noise level due to the radio emission of the atmosphere and of the earth.[76]

3. Cosmic Radio Emission Measurement Procedures

The main problem in radioastronomical observations in the centimeter band is the determination of the antenna parameters. At millimeter wavelengths, there is added to this problem the need for taking accurate account of atmospheric absorption. The procedure of determining the antenna parameters is considered in detail in the monographs.[143, 144]

If the atmospheric absorption is sufficiently small, it can be calculated from meteorological data, and the measurement procedure in this case is analogous to that used at centimeter wavelengths.[145] The most accurate method of absolute measurements of the intensity of radio emission of extraterrestrial sources is in this case the "artificial moon" method,[146] which was successfully used also in the millimeter band[147] for observations performed at high altitudes. The accuracy of this method can reach several percent. The "artificial moon" method is based on comparing the radio emission of the investigated object with the thermal emission of a standard of suitable dimensions, located in the Fraunhofer zone of the antenna. The largest millimeter-band antennas are so large that D^2/λ amounts to several times ten kilometers. It is necessary to place the standard in the Fresnel zone, and accordingly to move the radiator out; this, as shown in [148], is equivalent to the first method.

Atmospheric absorption is determined usually on the basis of known experimental data[129] on meteorological parameters measured on earth, and from their altitude distributions obtained with the aid of radiosondes. Measurements of atmospheric absorption by one of the known radioastronomical methods[149] are sometimes made simultaneously with the observation of cosmic radio emission.

If the atmospheric absorption is large, then good results are obtained by comparing the investigated radiation with the brightness temperature of the atmosphere.[52] The antenna temperature is determined from the relation

$$T_A = q_0 T_a [1 + wHT_a^{-1} S(\gamma) + \Delta_T], \qquad (6)$$

where q_0 is the ratio of the difference of the readings at the output of the radiometer when the antenna is aimed on the source and on the region of the sky next to it, to the difference between the readings when the antenna is aimed on the sky next to the source and on the region with temperature T_a. Δ_T is a correction that takes into account the anisotropy of the distribution of the lateral and backward radiation of the antenna. A procedure for determining this correction is discussed in [52, 54]. The accuracy of the determination of Δ_T and of the principal lobe of the antenna of the radiotelescope determines the total error of the method, which usually amounts to about 10–15%.

Numerous measurements of the radio emission of the moon in a wide range of wavelengths, from decimeter waves to submillimeter waves,[220] have made it possible to use now the moon as a radio-emission standard. However, in observations of sources with small angular dimensions by means of high-directivity antennas it is necessary to know the directivity pattern within the limits of the dimensions of the lunar disc. The resultant accuracy is not better than 20–25%.[16, 58] Therefore the best method of measuring radio emission fluxes from extraterrestrial objects is by comparison with the radiation from the planets.[58, 144, 145] In this case the accuracy of the measurements is determined, in practice, by the uncertainty with which the brightness temperatures of the planets are known. Obviously, the most suitable standards are planets with rarefied atmospheres (Mercury and Mars), for in this case the probability of a considerable spontaneous variation of their emission is smallest.

The distributed cosmic radiation is measured in the millimeter and submillimeter bands with the aid of small antennas (usually horn antennas[9, 115]) by comparing the radiation from the sky with radiation of a cooled load. The measurement method used in the centimeter band is analogous to the "artificial moon" method and is based on replacing the section of the sky with standards having different temperatures.[152] The latter method is used also in the millimeter band.[149–151] Procedures for radioastronomical investigations outside the atmosphere are considered in [1].

IV. RADIO EMISSION OF THE SUN

Experimental data on the radio emission of the sun, and also their interpretations, are discussed in detail in the monograph[3] and in the review.[153, 154] Some information concerning the brightness temperature of the sun at millimeter and submillimeter wavelengths is given in [155–157]. In this connection, principal attention will be paid to an analysis of the latest experimental data and to a discussion of problems involved in further investigations of the solar radio emission in the band of interest to us.

1. Radio Emission of the "Quiet" Sun

Recently much experimental material has been accumulated concerning the integral radiation from the solar disc in the millimeter (and in part also the submillimeter) band; insofar as we know, this material has not yet been properly analyzed. Table V gives an idea of the amount of this material. It should be noted that it is extremely uneven. The data on the brightness temperature of the solar disc obtained prior to 1958–1960 should be taken with great caution. At that time the procedure for absolute measurements of the intensity of the radio emission was not yet sufficiently well developed, and in the first such measurements there were frequent errors in the determination of the parameters of the antennas and in the allowance for the atmospheric absorption. Examples are [158, 159, 163] where no account was taken of the scattering of the antennas outside the principal lobe, and as a result the values obtained for the brightness temperatures of the sun at wavelengths 4 and 8 mm are too low. The data of [158, 163] were subsequently corrected.[160, 161, 179] In [181] there is an obvious error—the atmosphere of the earth was assumed to be isothermal, and this yielded too low a value for the atmospheric absorption, resulting accordingly in too low a brightness temperature of the sun at λ = 6 mm.[67]

The plot of Fig. 6 is based on the data of Table V. The dimensions of the shaded circles in the figure are inversely proportional to the measurement error. In those cases when the measurement error is unknown, the data are represented by a light circle. It is seen from Fig. 6, that the most reliable data on the brightness temperature of the sun were obtained in the IR region and at λ = 4 mm. The radio emission of the sun has been well investigated in the vicinity of λ = 1 mm and in the wavelength interval 8–15 mm.

The radio emission of the "quiet" sun at millimeter and submillimeter waves is generated in the lower layers of the chromosphere and characterizes the distribution of the temperature in these layers, since it is thermal by nature. Using the plot of Fig. 6, we can determine the temperature regime of the chromosphere. However, the solution of this problem entails considerable difficulties. First, it is necessary here to solve an integral equation of the type[162]

$$T_\odot(\lambda) = \int \varkappa_s(\lambda, n_e(h), t_e(h))\, t_e(h) \exp\left(-\int \varkappa_s\, dh\right) dh, \qquad (7)$$

where κ_s is the absorption coefficient of the solar plasma, t_e is the electron temperature, and h is the height over the photosphere. The solution of Eq. (7) is itself not a simple task; in addition, it is aggravated by the large scatter of the experimental data on $T_\odot(\lambda)$. In [162] there was proposed an approximate method of solving Eq. (7). The obtained $t_e(h^*)$ dependence is very close to the function $T_\odot(\lambda)$, where h^* is the height of the layer with optical thickness $\tau_\lambda \sim 1$. Thus, from the

Table V. Data on the brightness temperature of the sun

λ, mm	$T_{\odot}$, °K	Reference	λ, mm	$T_{\odot}$, °K	Reference
0.004	5626±100	165	3.4	8600±1000	67
0.005	5270±150	165	3.4	8200±1000	199
0.0086	5160±40	166	3.6—4	7000±350	178
0.0111	5036±30	167	4.1	8000±700	52
0.0167	4890±390	168	4.1	7300±200	147
0.02	4820±370	168	4.3	7000±700	179
0.025	4740±350	168	4.3	9600±500	174
0.0333	4640±330	168	4.3	7100±200	180
0.05	4500±300	168	5.5	6900±600	156
0.1	4270±240	168	5.61	6750±600	156
0.74	5200±1000	169	5.62	6500±600	156
0.87	5350±800	169	5.62	6100±600	156
1.0	5900±500	91	5.62	6900±600	156
1.0	5400±350	197	5.74	6900±500	156
1.06	5750±600	169	5.75	5700±1000	199
1.2	5600±400	170	5.8	6000±2500	67
1.24	5600±800	169	6.0	5000	181
1.26	6000±500	169	6.20	6100±1300	67
1.3	5900±400	170	6.2	8600±1000	199
1.45	6000±700	169	6.8	10000±1000	199
1.8	5300±700	171	6.8	8850±1500	67
1.8	6500±700	172	7.5	6600±700	182
2.0	5670±230	173	8.0	7500±900	160
2.15	5433±500	174	8.0	7500	183
2.2	6800±400	170	8.6	10420±730	184
2.25	5600±400	175	11 8	8870±980	185
2.4	6500±400	170	11.8	9800±700	186
2.73	5500±715	174	12.8	10700±700	188
2.8	6800±500	170	13.5	11000±700	186
3.0	5870±950	174	14.3	10800±700	186
3.2	6402±215	176	15.8	10800±700	186
3.3	6375±574	177			

point of view of [162], $T_{\odot}(\lambda)$ corresponds approximately to a certain averaged distribution of the electron temperature in the lower chromosphere. Second, it is not clear how the turbulences in the solar atmosphere affect the brightness temperature of the sun in the millimeter band. As shown in [164], the spectrum of the "quiet" sun can have singularities due to the scattering of radio waves by plasma turbulences. This question could be clarified by investigations of the distributions of the radio brightness over the solar disc at different wavelengths in the millimeter and submillimeter bands.

Let us return to the plot of Fig. 6. The $T_{\odot}(\lambda)$ plot has apparently two minima, one in the vicinity of $\lambda = 100-200\ \mu$ and the other near $\lambda \sim 6$ mm. The existence of the first minimum* is evidenced by the data[168] (together with other data on the radio emission of the sun), where results are reported of experimental investigations of the solar emission at submillimeter wavelengths, obtained with the aid of apparatus mounted on a balloon.** A "long-wave" minimum was observed in [67, 181]. The latest data[156] show that the brightness temperature of the sun is minimal at $\lambda = 5.6$ mm. However, the appreciable scatter in the data on the brightness temperature of the sun in the vicinity of $\lambda \approx 6$ mm makes it necessary to measure carefully the solar spectrum in this region.

If the $T_{\odot}(\lambda)$ plot actually reflects the altitude variation of the averaged electron temperature in the sun's atmosphere, then this should affect the form of the distribution of the radio brightness of the solar disc.[162] In the wavelength range $\lambda \sim 6$ mm there should be observed a "brightening on the edge," and in the interval

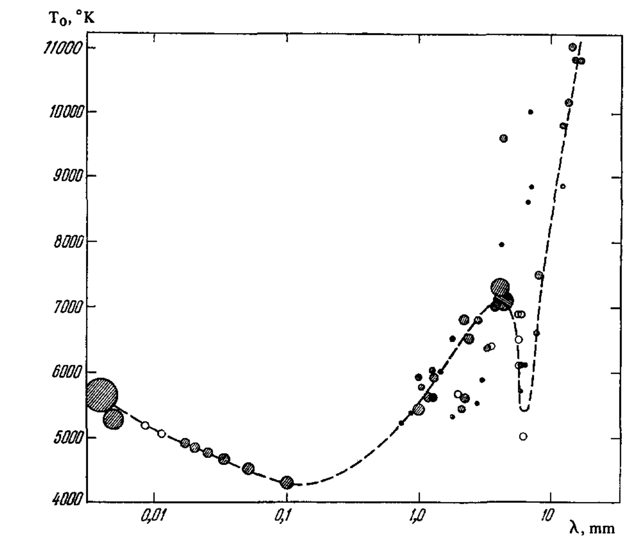

FIG. 6. Spectrum of the "quiet" sun in the millimeter, submillimeter, and infrared bands.

4 mm < λ < 6 mm there should be observed a "darkening towards the edge." At 0.2 mm < λ < 4 mm, the brightness distribution will have again two maxima near the solar limb ("brightening on the edge"). Experimental data on the distribution of the brightness over the solar disc are still few in number. Several investigations[187-191] show that at $\lambda = 8$ mm there exists brightening on the edge. Observations of the sun during eclipses at $\lambda = 4.3$ mm have made it possible to establish the existence of brightening at this wavelength, too.[190, 163] Different attempts to observe brightening on the edge at $\lambda = 3.2$ mm gave different results, namely, negative in some,[157] and affirmative in others.[190, 156] Finally, there are data indicating that the brightness distribution over the solar disc has the same character at 1.2 mm.[192] The brightening on the edge at

*The existence of a minimum in the electron temperature at 470–650 km above the photosphere is indicated also by the results of investigations of the structure of the optical lines of calcium [198].

*We note that in [168] there was obtained only the spectrum of the sun, and the absolute values of its brightness temperature were calculated from data obtained by IR observations.

$\lambda = 1.2$ mm does not contradict the general character of the $T_{\odot}(\lambda)$ plot (Fig. 7). At IR wavelengths, judging from this plot, there should be darkening towards the edge. The data of [192] confirm this conclusion: darkening towards the edge of the sun was observed at $\lambda = 24.3\ \mu$.

Unfortunately, no such observations were carried out in the wavelength interval 6–7 mm, which is of great interest for investigations of the brightness distribution. If the "dip" in the solar spectrum near $\lambda = 6$ mm is due to scattering of radio waves by plasma turbulence, then a darkening of the solar disc towards the edge should be observed in the entire region of the "dip." Another experiment capable of revealing a reflecting layer in the solar atmosphere is radar sounding of the sun at millimeter wavelengths.

It should be noted that the data of Table V were obtained by different observers at different phases of the 11-year solar cycle. Their classification as belonging to the "quiet" sun is therefore highly arbitrary. As will be made clear in the next section, the integral radio emission of the sun can vary in a wide range, depending on the number of active centers on the disc.

In conclusion, a few words on the possible interpretation of the spectrum of the solar radio emission at millimeter wavelengths. The existence of at least one minimum of the electron temperature in the sun's atmosphere is beyond any doubt.[153] It can be assumed that the maximum of the brightness temperature in the vicinity of $\lambda = 4$ mm is due to some absorption mechanism of resonant character in layers higher than the solar-atmosphere layer with $\tau_{\lambda = 4\ \mathrm{mm}} \approx 1$. One of the possible absorption mechanisms is dielectronic recombination of multiply ionized atoms in the solar corona.[193] The most intense lines of the dielectronic recombination lie in the region 1–10 mm. In the case when the increase of the brightness temperature in the vicinity of $\lambda = 4$ mm is indeed due to radiation from an optically thin layer in the solar corona, the brightness distribution over the sun's disc should have brightening on the edge in the entire region of the maximum (this is not contradicted by the available data on the distribution of brightness at $\lambda = 4.3$ mm[156, 190]). In addition, this should be reflected in the radio dimension of the sun, which may turn out to be larger than at $\lambda = 6$ mm. To obtain reliable data on the spectrum of the "quiet" sun (one cannot exclude the possibility that the maximum in the vicinity of $\lambda = 4$ mm is "accidental," as a result of variations of the solar radio emission) it is necessary to carry out absolute measurements of its radio emission by the "artificial moon" method[146, 147] or by comparison of the sun and the moon[178] in period of minimum solar activity.

2. Variations of the Solar Radio Emission

Until recently it was assumed that the slow component of the sporadic radio emission of the sun in the region $\lambda \lesssim 4$ mm makes a contribution on the order of a fraction of 1% to the integral radio emission.[3] This opinion was based both on some theoretical premises (see, for example, [194, 195]) and on the experimental data available at that time.[196, 200] The results of investigations of the s-component of the radio emission from the sun, performed recently with antennas having high resolution[157, 160, 161, 190, 201-205] show that slow variations of the integral flux density of the solar radio emission can be of the order of 10%. This is also indicated by a comparison of the brightness temperatures of the sun and the moon in the wavelength interval 3.6–4 mm.[178]

On the basis of the experimental data on the slow component of the radio emission of the sun in the millimeter band (it has not yet been investigated in the submillimeter band) we can draw the following conclusions concerning the characteristics of the emission of the active regions in the 2–16 mm range:

1) The spectra of the radio intensities of the active regions are quite varied. Regions identified with dipolar or multipolar groups of spots have an approximate λ^{-2} spectrum in the wavelength interval 2–4 mm. At 6 mm $< \lambda <$ 16 mm the emission intensities of these regions are approximately constant. Radio sources above the flocculas have a spectrum close to λ^{-2} in the wavelength interval 2–8 mm.[203]

2) The dimensions of the active regions approximately coincide with the dimensions of the corresponding optical formations on the disc of the sun (groups of spots and calcium flocculas). With decreasing wavelength, the dimension of the radiating region increases.[203]

3) There is no directivity of radiation.

Data on the polarization of the radio emission of the active regions in the millimeter band are still few in number. A circular polarization of the emission of active regions was observed over groups of spots.[205] The degree of polarization was 0.5–2%.

On going from centimeter to millimeter waves, a characteristic change takes place in the brightness distributions over the active regions. At 8 mm, just as in the centimeter band, this distribution has a central bright nucleus and a more extended but less bright halo.[160, 205] In the region $\lambda < 8$ mm, the nucleus vanishes and the brightness distribution becomes close to Gaussian.[203]

Another curious phenomenon is the existence on the sun of regions of decreased radio brightness compared with the level of the "quiet" sun), first observed at $\lambda = 8$ mm.[205] The regions of decreased radio brightness are identified with dark filaments (protuberances). The contrast of the cold regions decreases with decreasing λ[203] (see also Fig. 7). It was also noted that regions of decreased radio brightness correlate with regions where the magnetic field is small or zero.[176]

Experimental data on the spectrum of the slow component indicate that it has a maximum in the vicinity of $\lambda = 3$ cm;[3, 195] with decreasing λ, a drop occurs in the flux density of the s-component. In the region $\lambda = 8$–30 mm, the flux density of the s-component is approximately constant,[160] and then begins to increase with decreasing λ. The known models[3, 194, 195, 206] do not present a complete description of the spectrum of the slow component. In the millimeter band, sources of increased radio emission on the sun are optically thick and their radiation should be of the bremsstrahlung type. In [176] there was observed a correlation between the regions of increased radio brightness and the regions of strong magnetic fields. However, the magnetic fields required in order for the synchrotron radiation

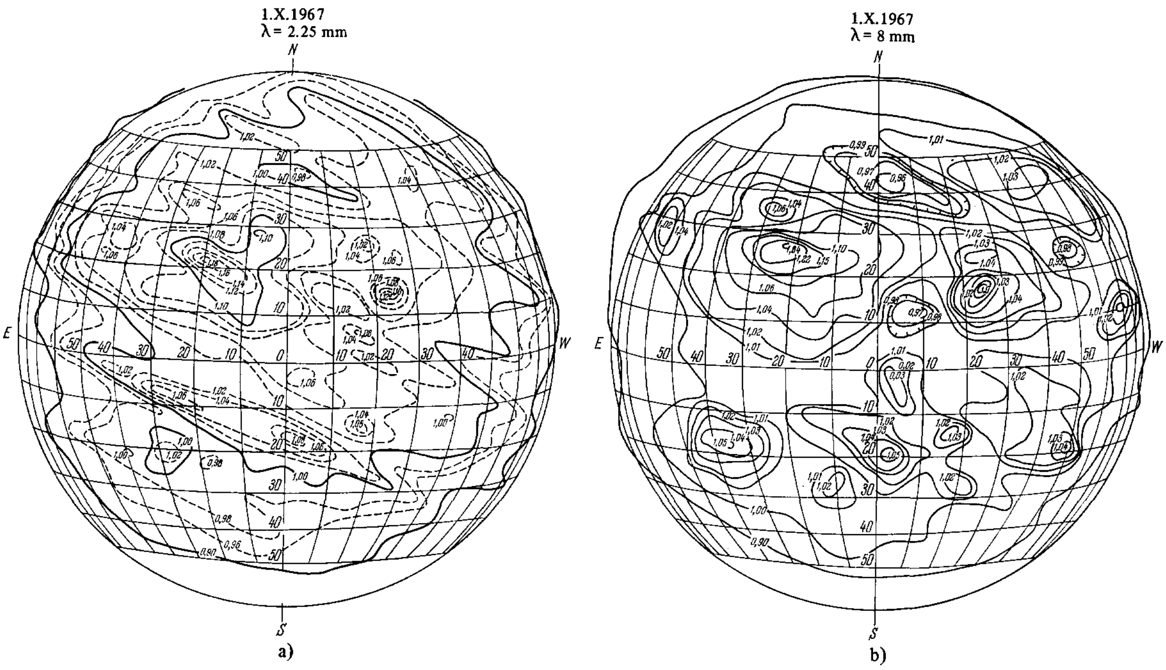

FIG. 7. Radio images of the sun, obtained simultaneously at the wavelengths λ = 2.25 mm (a) and λ = 8 mm (b) [203].

in the millimeter band to be appreciable are too strong.[194] The observed partial polarization of the radio emission of active regions on the sun at λ = 8 mm is evidence that at this wavelength there is still a noticeable contribution of the synchrotron-radiation component. It is possible that the synchrotron radiation comes from the central core of the source.

We note that the results of calculations of the spectrum of the slow component are usually compared (of necessity) with the average data on the emission intensities of different active regions on the sun,[3, 195] whereas it would be more correct to compare the spectrum of the model with the spectrum of one and the same source. At the present time investigations are under way of the s-component simultaneously at several wavelengths in the millimeter band,[160, 161, 190, 202, 203] and such a possibility will soon be realized.

Interesting results should be obtained from investigations of the radio emission of groups of spots with the aid of a high-resolution radiotelescope (~ 1″). Such observations would answer the question whether individual spots can be resolved in the radio band. This calls for polarization measurements of the brightness temperatures of the regions of increased radio emission, and also of measurements of the heights of the active regions above the photosphere.

In concluding this section, let us consider the available data, which are still few in number, on the observation of solar flares at millimeter wavelengths. The first observations revealed the very fact that there exist short-duration increases of solar radio emission, correlating with optical flashes and with bursts of radio emission at longer wavelengths.[207-209] The flashes could be reliably localized only after radio telescopes of high resolution came into use.[210] As shown in [211], at a wavelength λ = 8 mm there are observed flashes of radio emission of all three types, A, B, and C. All these flashes were identified with chromospheric flares. The spectra of the flashes of radio emission at millimeter wavelengths have hardly been investigated. It is known that the maxima of these spectra lie in the centimeter band.[212, 213] Some data on the spectrum of a type-A flash in the interval 2–8 mm are contained in [203]. We note that observations of flashes of radio emission, which are usually highly localized, with the aid of sharply-directional antennas is not a simple matter and calls for the use of a special procedure.[214]

A very unusual phenomenon in the observation of the sun at λ = 1.2 mm has been noted in [214], where rapid changes (with periods ~ 1 min) were observed in the brightness temperatures of active regions. However, there is no information in [214] concerning any control experiment that would convince the authors that the fluctuations of the atmospheric absorption might not be the cause of the observed phenomenon. Broadband thermal receivers are particularly sensitive to changes in the water-vapor content of the atmosphere, since resonant lines of H_2O can fall in their operating band.

* * *

Certain problems in the investigations of radio emission from the sun in the millimeter and submillimeter bands were already mentioned above. We now wish to supplement them somewhat.

As seen from Fig. 6, there are no data on the radio emission from the sun in the wavelength interval 0.1–0.7 mm. Observation of the sun at these wavelengths were carried out,[215-217] but its brightness temperature was not measured. Yet this is necessary in order to obtain more detailed information on the temperature distribution above the photosphere, and particularly to refine the position of the first minimum in the brightness-temperature spectrum of the sun. It would be also of interest to observe the sporadic radio emission of the sun in the submillimeter band.

The most interesting problem occurs in observa-

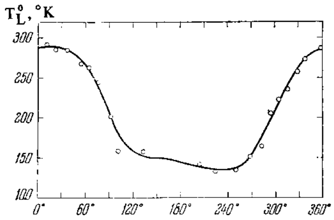

FIG. 8. Dependence of the brightness temperature of the central part of the lunar disc on the phase at $\lambda = 2.25$ mm [175].

Thus, observation of eclipses and lunations have made it possible to compare the properties of the lunar matter in layers differing in thickness by almost one order of magnitude. The thermal parameter $(k_L\rho_L c)^{-1/2}$ changed in this case by approximately a factor of two, thus pointing to the existence of a weak inhomogeneity in the lunar surface.[220]

Inasmuch as the lunar-crust layer responsible for the radio emission at millimeter and submillimeter waves is quite thin, appreciable temperature changes occur in it during the time of lunation, and the dependence of the thermal conductivity of the lunar matter on the temperature is therefore important.[233-235] The temperature dependence of the thermal conductivity produces a temperature gradient in a lunar-crust layer with thickness on the order of l_T.[234] From the value of the gradient it is possible to estimate the degree of the $k_L(T)$ dependence, and also to obtain information on the microstructure of the lunar matter, since the dependence of the thermal conductivity on the temperature is due to radiative transport of radiation.[233] It was established that $k_L(T) = k_{LO}(1 + 4 \times 10^{-6}\, T^2)$, where k_{LO} is a certain constant.[220]

The high resolution of the radiotelescope at millimeter and submillimeter wavelengths makes it possible to investigate the thermal and electrical parameters of individual sections of the lunar surface. From observations of the phase variation of the radio emission of the moon at wavelengths 3.2, 4, and 8 mm, with high angular resolution,[236-240] it was deduced that there are slight differences in the physical properties of the "continental" and "marine" regions (on the order of 25% in the parameter $(k_L\rho_L c)^{-1/2}$).

Observations of the radial distribution of the polarized radiation over the lunar disc at 8 mm wavelength have made it possible to determine the dielectric constant of the lunar surface and the degree of its roughness.[238] The maximum polarization was 4%, which is much less than at centimeter wavelengths. This is due to the roughness of the lunar surface. The large-scale roughnesses have, according to radiometric observations of the moon, an effective inclination angle of about 15°. Allowance for the diffuse scattering of the radio waves from the small-scale inhomogeneities of the lunar surface has made it possible to determine the dielectric constant of lunar matter, $\epsilon = 2.3 \pm 0.5$,[238] which is in good agreement with the radar determinations of this quantity at $\lambda = 8.6$ mm.[327]

The physical parameters of the upper layer of lunar matter, obtained on the basis of a detailed analysis[220] of the aggregate of observational data on the radio emission and IR emission from the moon, are in good agreement with lunar investigations performed with the aid of the automatic equipment on "Luna-9," "Luna-13," the five "Surveyors," the "Ranger" apparatus, and also orbiting lunar stations. Thus, the moon has become an object with which, in essence, terrestrial methods of investigating planets that have no sufficiently dense atmosphere have been verified (and confirmed). This gives grounds for expecting success also in the study of Mercury and Mars by radioastronomy methods. The physical conditions on these planets are apparently similar in many respects to those on the moon, as is evidenced by data of optical observations and radar observations of Mercury and Mars (and also the photographs of "Mariner-4").

2. Mercury and Mars

Observations of Mercury are made difficult by its proximity to the sun and its relatively small angular dimensions. It is not surprising that its first observations at centimeter[241] and millimeter[242, 243] wavelengths did not reveal reliably the phase dependence of the radio emission of Mercury, although some indications of its existence were obtained in [242].

Reliable data were obtained recently on the phase variation of the radio emission of Mercury at wavelengths $\lambda = 3.4$ mm,[244] $\lambda = 8$ mm,[246] and $\lambda = 19$ mm.[245] These data, however, cannot be reconciled[235, 247] with each other within the framework of the radio-emission theory developed for a homogeneous model of the moon, with thermal parameters that do not depend on the temperature. As shown in [247, 248], the phase effect of Mercury depends significantly on the position of the planet in its orbit (owing to the strong eccentricity), and it is necessary to take into account in its calculation the dependence of the thermal conductivity of the material on the temperature. Further development of the theory of radio emission from Mercury is hindered by the fact that the nighttime temperature of its surface is unknown, and there are only data on its upper limit.[249]

In [326] an attempt was made to interpret the available data on the radio emission of Mercury with allowance for the dependence of the thermal conductivity of its matter on the temperature. It turned out that the parameter $(\delta/\lambda)_M$ lies in the range 0.7–1.5 cm^{-1}, i.e., it is close to that obtained for the moon. More appropriate for the comparison of different planets is the product of δ/λ with the square root of the insolation period (the value of this product does not depend on the physical properties of the substrate), which amounts to (0.7 ± 0.3) $cm^{-1}\, yr^{1/2}$ for Mercury[326] and 0.9 $cm^{-1}\, yr^{1/2}$ for the moon.[235, 239] These conclusions concerning the proximity of the physical properties of the surface layer of the lunar matter and that of Mercury are based on observations of the planet in the centimeter band. Observations at millimeter wavelengths give significantly different results ($(\delta/\lambda)_M = 0.1$ cm^{-1} [246] at $\lambda = 8$ mm and 3.3 cm^{-1} [326] at 3.4 mm), but the latest data still have to be refined. From the spectrum of the average brightness temperature of Mercury it is possible to determine a parameter characterizing the dependence of the thermal conductivity of its matter on the temperature, but the accuracy of the available experimental data does not make it possible to do so with sufficient assurance. This is a problem for the future.

tions of the solar radio emission in the millimeter band. This band contains the lines of dielectronic recombination and also the lines of rotational spectra of many molecules contained in the solar atmosphere. In particular, the radio lines of carbon monoxide, the presence of which in the solar atmosphere is revealed by optical methods,[218] and of lines of other molecules,[219] should be observed.

V. INVESTIGATIONS OF THE MOON AND OF THE PLANETS

In both the Soviet and in the foreign literature there are periodically published monographs[3,4,7] and reviews[220–223] devoted to the results of radioastronomic observations of the moon and of the planets. We shall pay here principal attention to the problems peculiar to the bands of interest to us, and also to the future research trends.

1. The Moon

The brightness temperature of the surface element of the moon, as a function of the phase, varies like

$$T_{л}(\varphi, \psi, t) = [1 - R(\varphi, \psi)]\{T_0(\psi) + \sum_{n=1}^{\infty} (-1)^{\alpha_n} \frac{T_n(\psi)\cos(n\Phi - n\varphi - \varphi_n - \xi_n(\varphi, \psi))}{\sqrt{1 + 2\delta_n \cos r' + 2\delta_n^2 \cos^2 r'}}, \quad (8)$$

where t is the time, φ and ψ are the selenographic longitude and latitude, $R(\varphi, \psi)$ the reflection coefficient of the moon's material, $T_0(\psi) = T_{nt} + 0.387(T_{dt} - T_{nt}) \times (\cos\psi)^{1/2}$, where T_{nt} and T_{dt} are the nighttime and daytime temperatures on the surface of the moon; $T_n(\psi) = T_n \cos^{i(n)}\psi$, where T_n and i(n) are determined by the dependence of the surface temperature on the latitude,[227] $\alpha_n = (n-1)(n-2)/2$, $\Phi = \Omega t$, where Ω is the lunation frequency, and φ_n is the phase shift for n-th harmonic of the surface temperature relative to the insolation. $\delta_n = l_e/l_{p.t}$ is the ratio of the depth of penetration of the electric and thermal waves into the lunar matter, with $l_{p.t} = (2a/n\Omega)^{1/2}$, where $a = k_L/\rho_L c$ (k_L is the thermal-conductivity coefficient, ρ_L is the density, and c is the specific heat of lunar matter). The factor $\cos r' = (\epsilon - \sin^2 r)^{1/2}/\epsilon^{1/2}$ is connected with refraction on the moon-vacuum interface (ϵ is the dielectric constant of the medium and r is the angle between the line of sight to an element and the normal to the surface at the point (φ, ψ)). The phase shift $\xi_n(\varphi, \psi) = \tan^{-1}[\delta_n \cos r'/(1 + \delta_n \cos r')]$ determines the delay of the maximum of the radio emission relativity to the maximum of the surface temperature of the element (φ, ψ).

Equation (8) was obtained under the assumption that the surface layer of the moon is homogeneous and its physical parameters do not depend on the temperature. It is seen from (8) that the dependence of the brightness temperature of the lunar surface element on the time is quite complicated. The antenna of the radiotelescope receives radiation from a certain lunar-disc segment having a brightness temperature T_L, and the brightness temperatures of the individual elements become averaged out. As is shown in [228], the averaging leads to a decrease of the relative weight of the higher harmonics of the function $\bar{T}_L(t)$, and in investigations of the radio emission from the moon by means of radiotelescopes of low directivity ($\Delta\varphi \gtrsim 30'$) the function $\bar{T}_L(t)$ is nearly sinusoidal. If $l_e \gg l_{p.t}$, then obviously at such a ratio of the depth of penetration of electric to thermal waves (which is usual for the centimeter band) the contribution of the higher harmonics to (8) is much smaller than when $l_e \ll l_{p.t}$.

Experiment shows[52, 54, 147, 172, 175, 239] that $\delta_1/\lambda \sim 1$ in the millimeter and submillimeter bands (if λ is in centimeters), i.e., $\delta_1 \ll 1$ (if $\lambda \lesssim 4$ mm). Thus, the radio emission of the moon at these wavelengths comes from a surface layer whose thickness is much smaller than the depth of penetration of the first harmonic of the thermal wave. The character of variation of the brightness temperature of the moon at millimeter wavelengths during the time of lunation is similar to the phase dependence of the surface temperature. An example is the plot in Fig. 8, which shows the phase variation of the radio emission of the central part of the lunar disc, measured at λ = 2.25 mm.[175] In the millimeter and submillimeter bands it is possible to analyze not only the first but also the higher harmonics of the phase variation, if the observations are carried out with an antenna having a sufficiently high resolution.[54, 224, 225] The very first detailed investigation of the second harmonic of the phase variation of the radio emission from the moon at λ = 8 mm [232] has made it possible to determine the latitude distribution of the temperature over its disc. Similar results were obtained on the basis of data on the phase variation of the radio emission from the moon at λ = 4.1 mm in [225], where the latitudinal distribution of the surface temperature was also investigated, and turned out to be nearly proportional to $(\cos\psi)^{1/2}$. The ratio $l_e/l_{p.t}$ can be determined for different harmonics[50, 175] and this makes it possible to determine the thermal parameters of the lunar matter in different layers. However, the available experimental data on the higher harmonics of the phase variation of the moon's radio emission are not yet sufficiently reliable.

More definite information on the character of the variation of the physical properties in the upper layer of lunar matter can be obtained by investigating the dependence of δ_1/λ on λ. As shown in [54], in the wavelength band 0.87–1.45 mm there is observed a change of the ratio δ_1/λ, indicating apparently an increase of the parameter $(k_L\rho_L c)^{-1/2}$ to a value $\sim 10^3$ at λ = 0.87 mm.* Independent data pointing to a similar character of the variation of the physical properties of lunar matter were obtained by observations of the radio eclipses of the moon at millimeter wavelengths,[230] as well as from observations of the variation of the surface temperature during the time of eclipses.[231] The thermal wave produced during the lunar eclipse penetrates to a depth smaller by a factor of 6–8 than the first harmonic of the thermal wave produced by lunation. Therefore the data of radio eclipse observations (which are sufficiently strongly produced only at wavelengths $\lambda \lesssim 1$ cm) characterize a lunar surface a few centimeters thick.

*Data on the radio emission of the moon at centimeter and millimeter waves correspond to $(k_L\rho_L c)^{-1/2} = 600$ (in the cgs system) [220].

Table VI. Brightness temperature of Mars

λ, mm	Brightness temperature, °K	Reference	λ, mm	Brightness temperature, °K	Reference
0.008—0.014	300±5	251	8,0	225±10	256
0,012	242	252	8,6	230±42	253
0.012	235±13	259	8,6	235^{+40}_{-35}	280
1,2	169±17	91	9,55	170±30	254
3.2	240^{+72}_{-48}	253	31,4	211±20	274
3,4	167±20	254	37,5	190±12	257
3.4	190±40	255			

The radio emission of Mars is also determined mainly by the thermal radiation of its surface. The theory of lunar radio emission can be used to determine the physical properties of the material of Mars.[215] However, the illuminated side of Mars always faces the earth (only about 15% of the area of the visible disc remains in the shadow). Therefore land-based observations can yield only the brightness-temperature spectrum of the side of Mars illuminated by the sun. As shown in [250], the section of the spectrum of the Mars radio emission containing the greatest amount of information is the band $0.1 < \lambda < 3$ cm. The available data on the brightness temperature of this planet (Table VI) are so far insufficiently accurate to be able to determine from them the parameters of Martian matter with sufficient reliability. It is shown in [250] that from the spectrum of the radio emission of Mars it is possible to determine the parameter $m = c_{Ma}(k_{Ma}\rho_{Ma}c_{Ma})^{-1/2}/2b(\epsilon_{Ma}\pi t_0)^{1/2}$, where b is the specific loss-angle tangent, ϵ_{Ma} the dielectric constant, and t_0 the period of insolation. The available experimental data on the brightness temperature of Mars correspond to $b = (1.1 \pm 0.6) \times 10^{-2}$ if it is assumed that $(k_{Ma}\rho_{Ma}c_{Ma})^{-1/2} = 170 \pm 80$ on the basis of results of IR observations of Mars,[252] and $\epsilon_{Ma} = 2.6 \pm 0.8$ from radar observations of Mars. It is most probable that the surface of Mars is made up of basic and medium rocks. Further observations of the planet in the wavelength band 0.1–3 cm are needed.

A study of the surface of Mars can be carried out quite effectively with the aid of radio telescopes mounted on artificial satellites of this planet. The brightness temperature distribution obtained on going through the terminator when orbiting around Mars can be used to determine the thermal and electric parameters of Martian matter.

3. Venus

A detailed review of the results of radioastronomical investigations of Venus was published relatively recently.[7] We present here therefore a very cursory discussion of some problems in radioastronomical investigations of Venus at millimeter wavelengths.

The radioastronomical data on the polarization of the radio emission from Venus at $\lambda = 10$ cm lead to the conclusion that the surface has a temperature of approximately 700° K.[7]

A successful study of this planet was initiated recently with the aid of automatic interplanetary stations ("Venus-4, 5, 6" and Mariner-2, 5"). It can now be regarded as established without doubt that in the lower atmosphere of Venus there also exists a layer with exceedingly high temperature (according to the data of "Venus-5, -6" this temperature is 400–530° C [260]). However, the mechanism whereby the surface of Venus becomes heated is still not clear. It is possible that this is the consequence of the hot-house effect[261] or of powerful atmospheric circulation,[262] or else of processes occuring on the surface of the planet itself.[268]

The brightness temperature of Venus at millimeter wavelengths is approximately half the surface temperature, this being due to absorption of these radio waves by the relatively cold atmosphere of the planet. Thus, the radio emission of Venus at millimeter and submillimeter wavelengths characterizes the distribution of the temperature in its atmosphere. An investigation of the phase dependence of the radio emission of Venus at millimeter wavelengths yields information on the variation of the temperature at the corresponding levels over the surface of the planet when the insolation changes, and is useful for a clarification of the heating mechanism. At infrared waves, the phase dependence is not observed reliably.[263]* The most complete data on the dependence of the brightness temperature of Venus $T_♀$ on the phase angle i is obtained at wavelengths 3.4, 8.6, and 31.5 mm

$$\left.\begin{aligned} T_♀(\lambda=3{,}4\ \text{mm}) &= [(296\pm1)-(11\pm2)\cos(i-1°\pm5°)]°\text{K},\\ T_♀(\lambda=8{,}6\ \text{mm}) &= [(425\pm2)+(10\pm4)\cos(i-12°\pm11°)]°\text{K},\\ T_♀(\lambda=31{,}5\ \text{mm}) &= [(621\pm5)+(73\pm6)\cos(i-11°,7\pm22°)]°\text{K}. \end{aligned}\right\} \tag{9}$$

As shown in [270], these data can be reconciled under the assumption that the atmosphere of Venus contains an aerosol in an amount 40% larger on the daytime side of the planet than on the nighttime side (the corresponding effective heights of distribution of the aerosol particles are 12 ± 2 and 8 ± 1 km). The temperatures on the daytime and nighttime sides of the planet should be 820 ± 10 °K at 620 ± 10 °K, respectively. The variations of the temperature on the surface explain the "positive" phase variation of $T_♀(i)$ at $\lambda = 8–31.5$ mm, whereas variations of the transparency of the atmosphere are admitted for the interpretation of the "antiphase" variation at the wavelength $\lambda = 3.4$ mm.

We note that there are published indications pointing to the existence of a "positive" phase effect at wavelengths $\lambda = 4.1$ mm[16] and $\lambda = 2.25$ mm.[271] A "positive" phase variation of the brightness temperature of Venus was also reported at $\lambda = 3.2$ mm and λ

*A slight excess of the brightness temperature of the dark part over the illuminated one has been observed (in the 8-14 μ band [264]).

Table VII. Brightness temperatures of Jupiter and Saturn

λ, mm	Brightness temperature, °K		Reference	λ, mm	Brightness temperature, °K		Reference
	Jupter	Saturn			Jupter	Saturn	
0.008—0.014	130	93 ± 3	275	8,6	113 ± 11	116 ± 30	253
1.2	155 ± 15	140 ± 15	91	8,6	149 ± 15	96 ± 20	278
2.11	170 ± 80	—	175	9,55	—	118 ± 20	254
8.2	111^{+22}_{-11}	97^{+52}_{-42}	253	11,8	123 ± 11	—	279
3.4	145 ± 23	—	281	12,8	116 ± 10	—	279
3.4	140 ± 16	130 ± 15	254	13,5	98 ± 10	—	279
3.87 *)	140^{+42}_{-33}	—	58	14,3	106 ± 11	—	279
4.3	105^{+18}_{-12}	103^{+70}_{-64}	253	15,3	—	146 ± 23	276
8,0	—	132 ± 9	256	15,3	150 **)	141 ± 15	282
8.35	144 ± 23	—	287	15,8	105 ± 21	—	279
8.6	142^{+14}_{-10}	—	280	19,0	180 ± 27	200 ± 30	283
				31,2	—	123 ± 16	284
				31,5	145	—	277
				33	193	—	286
				34,5	—	106 ± 21	285

*The temperature was corrected to take the ellipticity of Jupiter into account.
**Assumed constant.

= 4.3 mm.[237] It is difficult to say whether these results contradict the data of [265], since the selective character of the absorption in the layer of the Venus atmosphere above the clouds can lead to phase effects of opposite signs.[272] The brightness temperature of the nighttime side of Venus at $\lambda = 2.25$ mm is close to the temperature of its cloud layer;[18] consequently, these waves are absorbed by the clouds of Venus and only the radiation of the layer above the cloud and the variations of the temperature of clouds themselves can produce a phase effect. Spectral investigations of the $T_♀(i)$ dependence are needed both at millimeter wavelengths and in the IR band in order to clarify both the origin of the phase effect and the nature of the cloud layer of Venus.

4. The Giant Planets

Most investigations were devoted to the radio emission from Jupiter and Saturn. A characteristic feature of the emission of these planets in the millimeter band is that the brightness temperatures exceed the equilibrium values.[4] The contribution of nonthermal radiation is quite small, apparently, already at wavelengths $\lambda \lesssim 3$ cm,[3] so that the difference between the brightness and equilibrium temperatures in the millimeter band must be attributed to temperature gradients in the atmospheres of Jupiter and Saturn. To be sure, the accuracy of the available data on the radio emission of these planets at millimeter wavelengths (Table VII) is still insufficient for a reliable determination of the value of the gradient and its dependence on the wavelength.

A similar phenomenon was observed for Uranus and Neptune at $\lambda = 19$ mm.[288] The brightness temperatures of these planets turned out to be 220 ± 35 and 180 ± 40 °K, respectively, which is much larger than their equilibrium temperatures (60 and 40 °K respectively). The emission of Uranus at $\lambda = 20$ μ was investigated in [283], and its brightness temperature at this wavelength is 55 ± 3°K.

Jupiter is a very convenient object to use for the determination of the parameters of the antennas of large radiotelescopes by means of its radiation. The dimensions of Jupiter are sufficiently large and vary in relatively small limits. Recently published indications point to the existence of variability in the radiation of this planet at a wavelength $\lambda \approx 1.35$ cm.[289] It is not excluded that the brightness temperature of Jupiter experiences oscillations in the millimeter band, too (its optical picture is quite variable). This question calls for a thorough experimental verification.

In concluding this chapter we note that one of the principal problems of radioastronomical investigations of planets in the millimeter and submillimeter bands is radiospectroscopy of their atmospheres. Observations of the rotational lines of gases making up these atmospheres can yield information on the amounts of the various gases, and also on the physical conditions in the region of the formation of the line.[93]

VI. RADIO EMISSION OF DISCRETE SOURCES AND DISTRIBUTED COSMIC RADIATION

1. Discrete Sources of Radiation

An appreciable number of the known sources have a negative spectral index in the centimeter band, i.e., the flux densities of their radio emission decrease with increasing frequency f like f^{α}, where $\alpha < 0$. As already mentioned in Sec. 1 of Ch. I, the possibilities of investigating such objects are much more limited in the millimeter and submillimeter bands than in the centimeter band. With further development of observations at short centimeter and at millimeter wavelengths, sources with $\alpha \gtrsim 0$ were observed. Table VIII, in which data are summarized on the discrete sources of radio emission at millimeter wavelengths, gives an idea of the number of such objects. Table VIII does not include data on the sources Taurus-A, Sagittarius-A, and 3C 273, the results of investigations of which are discussed separately and are illustrated in Figs. 9–11.

Most sources listed in Table VIII have a flat spectrum or even a positive spectral index. This is natural, since objects with $\alpha \gtrsim 0$ are easier to observe in the millimeter band.

The very first observations of the most powerful quasar (3C 273) in the millimeter band[91, 292] have revealed considerable oscillations of the intensity of its emission. Whereas the flux density changes in 3C 273 observed in the centimeter band amounted to several

Table VIII. Discrete sources of radio emission

Source	λ = 3.4 mm		λ = 8.2 mm			λ = 9.55 mm		
	S, flux units	Reference	S, flux units	Dimension, ang. min.	Reference	S, flux units	Dimension, ang. min.	Reference
Orion-A	585±200	309	250±30	4′.2××4′.8	309	194±39	2′.2××2′.9	60
Cassiopeia-A						171±33	4′×4′	60
Virgo-A	5±2	291				20±5	1′×1′.5	60
DR 21	21±4	290				19		298
W 49	54±11	293						
3C 400						55±12	1′.4××1′.6	60
IC 418						1.7±0.9		297
NGC 7027						6.7±0.9		297
NGC 1068	10±3	296						
Cygnus-A	14±6	291				55±12	2′ *)	60
3C 84	23±3	291	26±7		295	29±5		60
3C 120	13±4	291						
3C 279	13±3	294	15±1		299	18±4		60
3C 345	11±3	291						
3C 446	6±4	291						
3C 454,3	15±3	291				14±3		60
4C 39,25	8±2	291						
NRAO 150			9,6±1		299	10±3		60
2145+06						4±1		294

*Two pointlike sources at a distance 2′.

times ten percent[301, 302], at λ = 3.4 mm the changes were by a factor 2–3. A certain correlation was observed between the changes of the flux density of the radio emission of 3C 273 at 3.4 mm with the oscillations of the brightness of the quasistellar object identified with this source.[291] Since changes of the radio-emission intensity of sources make it possible to estimate their dimensions and the distances to them (see, for example, [302]), this circumstance makes particularly attractive observations of quasars at millimeter wavelengths, whereas the variability becomes manifest more strongly than at centimeter wavelengths. However, there are considerable discrepancies in the data of different authors concerning the variations of the radio emission of 3C 273 at millimeter wavelengths, obtained during the same period of time (see, for example, the observation data obtained at λ = 3.4 mm[291] and λ = 8.2 mm[299, 303]. Measurements of the intensity of extraterrestrial radiation at millimeter wavelengths, as was already noted in Ch. II, are greatly hindered by the absorption of the radio waves in the atmosphere, and also by the fluctuations of the radio emission of the atmosphere. Errors are also produced by uncontrollable changes in the parameters of the antennas. In [291] is described a control experiment (observations of Saturn), performed to verify the correctness of the method of determining the intensity of radio emission of 3C 273 at λ = 3.4 mm. Oscillations of the antenna temperature from Saturn were observed, corresponding to changes of its flux by ±20 units (one flux unit = 10^{-26} W/m^{2}Hz). A variability of 3C 273 of the same order was noted in [291].

Observations of 3C 273 at λ = 8 mm, performed by different authors,[299, 303] yield different values of its flux, although the measurement method was the same—comparison of 3C 273 with Jupiter. All this makes it necessary to approach with caution the available data on the variability of the radiation of 3C 273 at millimeter wavelengths.

Figure 9 shows the spectrum of 3C 273, constructed from the data of [294, 304, 305]. In constructing the spectrum, we used the maximum observed values of the flux densities. The results of the observations of 3C 273 at

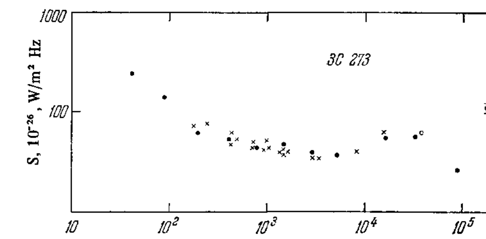

FIG. 9. Spectrum of radio emission of the quasar 3C 273 (from the data of [294,301,302,305]).

λ = 2.16 mm and λ = 8.15 mm[305] indicate that its flux increases when λ decreases from 3 to 2 mm, but this apparently does not agree with measurement data obtained at λ = 3.4 mm,[291] which point to an opposite variation of the spectrum in the wavelength interval 8–3.4 mm. The plot of Fig. 9 does not show the results of observations of 3C 273 at λ = 1.2 mm,[91] where changes of more than one order of magnitude were noted in the flux of this source. These changes do not correlate with the variations of the radio emission of 3C 273 at different millimeter wavelengths[56] and apparently are the result of incorrect allowance for the atmospheric absorption (the noted change was observed during the period from January to June 1965, at which time a seasonal change took place in the optical thickness of the atmosphere at λ = 1.2 mm, owing to the increased humidity of the air).

The spectrum of a source is determined, as is well known[306] by the energy spectrum of the relativistic electrons responsible for the emission, by their distribution in space, and also by the distribution and magnitude of the magnetic field in the generation region. Thus, data on the spectra of the discrete sources yield information on the physical conditions in the generation region. An optically thin source should, generally speaking (for a power-law energy spectrum of the electrons), have a constant spectral index. Variations of the spectral index are attributed to various factors: the inverse Compton effect, synchrotron losses, and self-absorption. A flat spectrum, similar to that observed for 3C 273, cannot be described by a power law, and therefore such sources must be represented as superpositions of several optically dense components with different spectral cutoff values on the low-frequency side, due to the synchrotron self-absorption (see, for example, [294]). The sources of the same group are 3C 84, 3C 454.3, 3C 279, 4C 39.25, and NRAO 150. Radio-interferometer observations with high resolution have also revealed the multicomponent structure of sources with flat spectra.[307]

Using the theory of synchrotron radiation, it is possible to determine the surface brightness of the source from the relation[294]

$$f_0 \sim 34\,(S_{\max}/\theta_0^2)^{2/5} B^{1/5}\ \text{MHz},$$

where S_{max} (in flux units) is the maximum value of the flux component with dimension θ_0 (in seconds of angle), B is the magnetic field in Gauss, and f_0 is the frequency at which the flux of the component is maximal. It is easy to verify that the components for which f_0 lies in the millimeter band yield maximal values of the surface brightness ($\sim 10^6$ and more for 3C 84 and 3C 273 at $B \sim 10^{-4}$ G). This estimate is an illustration of the extent to which millimeter-wavelength investigations of spectra of discrete sources are of interest. The theory of synchrotron radiation of objects with large surface brightness encounters considerable difficulty.[302, 308]

Sources having flat spectra are identified with such extragalactic objects as quasars (3C 273, 3C 279, 3C 345, 3C 446, 3C 454.3, 4C 30.25), with galactic cores (3C 84), or with compact galaxies (3C 120, NGC 1068). The similarity of the radio-emission spectra and the tremendous surface brightness give grounds for assuming that quasars and Seyfert galaxies constitute different stages in the evolution of the same object.[308] The source 3C 84 is apparently an intermediate rung in this evolutional ladder.[308]

The most intensely investigated galactic object is Taurus-A (3C 144, identified with the Crab nebula) and Sagittarius-A (center of galaxy). The Crab nebula, which is a remnant of the 1054 supernova, turned out to be the most powerful of the known discrete sources of radio emission in the millimeter band (compare Table VIII with Fig. 10). However, the data on its emission intensity in the 1.2–8 mm band are quite contradictory. A number of papers[53, 58, 309–311, 324] indicate that the radio-emission flux density increases with decreasing wavelength from 8 to 1.2 mm, whereas other papers[123, 126] indicate that this source has a negative spectral index ($\alpha = -0.26$[123]) all the way to $\lambda = 3.2$ mm. Most investigations of the Crab nebula were performed with high-resolution instruments, but its dimensions are not known with sufficient accuracy, and this is the main reason for the large scatter of the measurement data on its emission intensity. It is assumed in [123], for example, that the dimensions of 3C 144 are $(2.7' \pm 0.5') \times (3.0' \pm 0.5')$, and the radio-emission flux of the Crab nebula at $\lambda = 4.3$ mm is $S_{144} = 281 \pm 73$ flux units. The results of [103, 112] give much larger dimensions for 3C 144 at $\lambda = 8.6$ mm, namely $3.5' \times 4.55'$. Similar results were obtained in an investigation[299, 313] of the brightness distribution of the Crab nebula at $\lambda = 8.6$ mm. If we guide assume the data of [299, 312, 313] and take into account the fact that the brightness temperature of Jupiter is about 145 °K, then we obtain, according to the data of [123], a value $S_{144} = 580 \pm 150$ flux units for 3C 144 (this agrees, within the limits of errors, with the data of [310], where a value $S_{144} = 750 \pm 200$ flux units was obtained at $\lambda = 4.3$ mm).* The distribution of the radio brightness of the Crab nebula is insufficiently well known, and this also introduces an appreciable uncertainty in the data on this flux. It is usually assumed to be Gaussian.[123, 126] But if it is assumed to be uniform, then this increases S_{144} by approximately 20%. All the foregoing indicates that it is very urgent to carry out precision measurements of the distribution of the radio brightness and of the dimensions of the 3C 144 source at short millimeter wavelengths.

The spectrum of the Crab nebula (see Fig. 10) is well explained as being due to synchrotron radiation of relativistic electrons.[6] The increase of its emission intensity in the 1.2–8 mm region can also be explained within the framework of this theory.[6, 314]

The galactic center is possibly the only discrete source observed at submillimeter wavelengths ($\lambda = 0.1$ mm, see [315]). These observations gave a striking result: the flux density of its radio emission amounts to $(1.8 \pm 0.8) \times 10^{-19}$ W/m²Hz! The spectrum of the radio source Sagittarius-A in the 2–75 cm band can be satisfactorily attributed to a combination of synchrotron radiation of relativistic electrons in a magnetic field and thermal radiation of hot ionized gas[316] (see Fig. 11). The results of IR observations (1.6–3.4 μ)[317] are interpreted as the long-wave branch of the total emission of the stars forming the galactic core, with a temperature ~4000 °K. None of the foregoing mechanisms can produce the effect observed at $\lambda = 0.1$ mm, which exceeds the predicted intensity by 3–5 orders of magnitude (see Fig. 11). The radiation of the center of the galaxy at submillimeter wavelengths may be due to dust clouds having a temperature 20–30 °K (even in this explanation, the expected effect is weaker by approximately 30 times than the observed one). It is interesting that the observations of the galactic center at 8 mm[309] and 2.11 mm[53] agree ap-

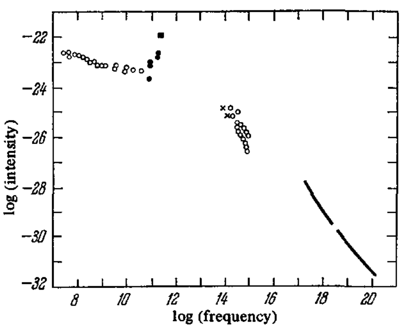

FIG. 10. Spectrum of electromagnetic radiation of the Crab nebula. The plots were taken from [325] and supplemented with data of [53,58, 309-311] (dark circles) and [324] (black square). The value of I is given in units of W/m²Hz.

*We note that in [123] the brightness temperature of Jupiter was assumed equal to 120 ± 20°C, whereas data on the observation of this planet at millimeter wavelengths (see VII) are closer to 140-150°K.

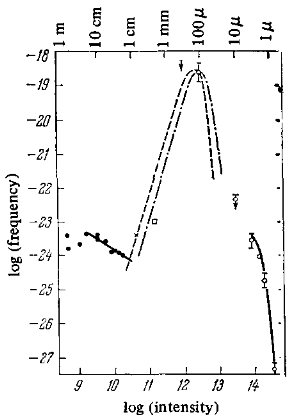

FIG. 11. Emission spectrum of the center of the galaxy. The plots were taken from [325] and supplemented with data of [53,309]. The dashed curve corresponds to black-body radiation with temperature 20°K, and the dash-dot curve to 30°K. The cross denotes data from [309] and the square, data from [53].

proximately with the result of [315] (see Fig. 11, the points for λ = 8 mm and λ = 2.11 mm fall on the Rayleigh–Jeans branch of the black-body radiation with temperature 20–30°K). To be sure, such a comparison is not quite correct, since the observation data for millimeter waves pertain to a relatively compact source with dimensions on the order of several minutes of angle, whereas the object observed at λ = 0.1 mm is extended (its dimension along the galactic plane is about 6.5°). Detailed investigations are needed of the galactic center, similar to those performed at centimeter wavelengths.[318]

From among the other objects investigated at millimeter wavelengths, particular interest attaches to the nebula in Orion (NGC 1275), the compact H II region of W 49 (the results of the observations will be discussed in more detail in Sec. 3 below), and also the planetary nebulas IC 418 and NGC 7027. The latter objects have typical thermal radio spectra (their electron temperatures are on the order of 10^4 °K [297]). The nebula NGC 7027 emits at IR wavelengths more intensely, by approximately one order of magnitude, than at λ = 9.55 mm, so that its observations in the 0.3–9 mm band should be of interest.

2. Distributed Cosmic Radiation

The nonthermal radio emission of the galactic background in the millimeter and submillimeter band is apparently so weak (its effective temperature varies in proportion to λ^3 [306]) that its value certainly lies below the sensitivity threshold of radiotelescopes. One can expect at millimeter and submillimeter wavelengths the existence of a noticeable radiation from clusters of matter, which is abundantly present in the galactic plane. This radiation should be similar in its character to the recently observed radiation of the galactic center at λ = 0.1 mm.[315]

In the millimeter band there is a maximum of the so-called "relict" cosmic radiation, the spectrum of which corresponds apparently to black-body spectrum with temperature of approximately 2.7°K.*

The "relict" radiation is exceedingly interesting from the point of view of cosmology.[41] Experimental data on the "black body" radiation are discussed in detail in [41], and much attention is paid to it also in the review.[1] We therefore confine ourselves here only to the remark that all the measurements performed to date of the brightness of the "relict" background fit within the model of "black body" radiation. The most definite evidence of this was obtained in measurements at wavelength 3.3 mm[9] and 3.58 mm.[150]

*"Relict" radiation is therefore called also "black body" radiation.

3. Monochromatic Radiation of the Galaxy

In the millimeter there was observed so far only one line, the recombination line of hydrogen H56α (frequency 36 466.32 MHz).[219] The line was observed in the emission of the Omega nebula. The temperature of the antenna at the center of the line was (0.31 ± 0.03) °K (the observations were performed with the RC-22 instrument of the Oka Radio Astronomical Station of the U.S.S.R. Academy of Sciences. The width of the contour was (3.8 ± 0.3) MHz, and the Doppler shift of the central frequency corresponded to a velocity (16.1 ± 1.2) km/sec of the radiating region. The electron temperature of the Omega nebula, according to data obtained at 8.2 mm, was found to be T_e = (9250 ± 1100)°K and much higher than the value T_e = 6000°K obtained from observations in the centimeter band.[320] It is possible[319] that this difference in the values of T_e is due to deviations from thermodynamic equilibrium. Thus, the observations of the recombination lines of hydrogen at centimeter and millimeter wavelengths make it possible to solve the fundamental problem of gas nebulas, namely to obtain the distribution of the hydrogen atoms over the energy levels. As is well known, the occurrence of maser effects is connected with level-population inversion.

Intense radiation of the sources Sagittarius-B2, Orion-A, and W 49 was observed recently in the 13.5 mm water-vapor line.[321] The last two objects radiate particularly intensely, and the corresponding antenna temperatures** are 14 and 55°K. It is not yet clear whether this is thermal radiation of H_2O vapor at high temperature (the electron temperature in the Orion nebula is approximately 8000°K [322]) or whether this is the maser effect analogous to that observed in the hydroxyl line. Measurements of the source dimensions in the H_2O 13.5 mm line, and also observations of other water-vapor lines in the millimeter and submillimeter bands, will make it possible to answer this question.

Highly promising are apparently observations of the lines of ammonia and formaldehyde, the presence of which in interstellar space was also observed recently (ammonia at the center of the galaxy at 12.652 mm,[57] and formaldehyde in the centimeter band in a number of sources[323]). These gases have rich rotational spectra at the millimeter and submillimeter wavelengths.

Attention is called to the fact that intense monochromatic radiation of water vapor and ammonia is observed in regions that are strong OH sources (such as W 49, the galactic center, and the source in Orion). Thus, an entirely new possibility of investigating the chemical evolution of interstellar matter is created.

**The 6-meter antenna of the University of California in Berkeley was used.

VII. CONCLUSION

The result of observations of the sun, planets, discrete sources, and distributed cosmic radio emission in the millimeter and submillimeter bands yield very important and interesting material for astrophysics. So far, the bulk of this material was obtained with the aid of earth-based instruments. In the future apparently, they raised the astronomical investigations at millimeter waves will also be carried out on earth (with the exception of certain special cases, such as the spectroscopy of very weak cosmic objects). Submillimeter waves are so strongly absorbed in the earth's atmosphere, that investigations in this band can be carried out effectively only with the aid of instruments outside the atmosphere.[1] To be sure, as shown by estimates in Sec. 1 of Ch. III, a radiotelescope for the submillimeter band, located at an altitude h = 3.5–4 km above sea level, can be used successfully for observations at wavelengths down to 0.4–0.5 mm, and if the altitude of the instrument is increased to 7–8 km, this will permit observations practically in the entire submillimeter band.

We wish to note certain problems faced by experimental radioastronomy at millimeter and submillimeter wavelengths. Foremost among these are spectral investigations of the sun, planets, discrete sources, and the distributed cosmic radiation. The observation and study of different absorption lines (or emission lines) of matter constitute, in our opinion, the most informative method of investigating the physical conditions in cosmic objects. As shown in Sec. 3 of Ch. VI, only the first steps were made in this direction, but they yielded quite unexpected results and uncover an entirely new possibility of investigating the chemical evolution of the galaxy. For most cosmological theories, an important role is played by the question of the existence of clouds of cold gas in the intergalactic space. It is necessary to search for absorption lines in the spectra of extragalactic objects, which can be realized most successfully at millimeter and submillimeter wavelengths.

The progress in the construction of large antennas and the improvements of the receiving apparatus will make it possible to receive in the nearest future the radio emission from the nearest stars. This will likewise be done most likely with the aid of an instrument operating at short centimeter and millimeter wavelengths.

We did not consider above problems involved in radar astronomy at millimeter and submillimeter wavelengths. So far, only radar sounding of the moon at millimeter wavelengths was accomplished (λ = 8.6 mm[327]). Many problems of radar astronomy at millimeter wavelengths are considered in the review.[328] We note here only that radar sounding of Venus can be realized at $\lambda \sim 1$ mm with the aid of a relatively small antenna ($D \approx 5$ m) and a low-power transmitter (power approximately 5–10 kW). This experiment will make it possible to determine the height of the cloud layer above the surface of the planet and to obtain information on the composition of the clouds in the atmosphere of Venus and their motion. A very enticing problem is an investigation of the spectrum of the reflectivity of the sun in the millimeter band (the search for the hypothetical reflecting layer). Estimates show that radar sounding of the closest stars will become realistic in the future. This will be of extreme interest for the determination of the exact position of the solar system and its motion in the galaxy. Interesting results can be obtained also from the search of reflecting objects outside the solar system, which are not revealed by their own radiation.

The problems of radioastronomical observations in the millimeter and submillimeter bands are considered also in the review.[1]

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