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EXTRA-ATMOSPHERIC SUBMILLIMETER ASTRONOMY *

A. E. SALOMONOVICH

P. N. Lebedev Physics Institute, U.S.S.R. Academy of Sciences

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I. INTRODUCTION

In recent decades the spectrum of electromagnetic radiation in which astronomical observations are conducted has been greatly extended. Besides the regions adjacent to the visible—the ultraviolet and the near infrared—the enormous radio range has been put at the service of astronomy. Recently it has been possible to use the shortest waves, x-rays and γ rays. Terms such as infrared astronomy, radio astronomy, x-ray astronomy, and γ-ray astronomy have come into widespread use. The classification according to the range of wavelengths providing information about objects in cosmic space is justified to the extent that the different ranges involve special methods for observing and analyzing the radiation, and also are applied to the solution of particular problems not accessible to other methods.

Until very recently there remained a single spectral region not yet "taken over" for astronomical use—the region intermediate between the radio range (millimeter waves) and the infrared range. This region, called the submillimeter range or the far infrared, is conventionally bounded by wavelengths 50 μ (or sometimes 100 μ) on the short-wave side, and by 1000 (in some cases 2000) μ on the long-wave side.[1] At present there is intense activity in this region, so that we may speak of the development of a submillimeter astronomy. The present paper is devoted to some problems and specific methods in this field.

Let us at once remark that one of the main reasons for the relatively late development of submillimeter astronomy has been the exceptionally unfavorable conditions for terrestrial astronomical observations in this range. The attenuation caused by the atmosphere makes it almost impossible to make observations at sea level on waves shorter than 1 to 2 mm. Therefore the broad development of submillimeter astronomy is now possible only because of the successes of rocket and astronautic technology, which make extra-atmospheric observations feasible. Accordingly, submillimeter astronomy will be largely based on extra-atmospheric observations. It is such observations that will concern us here.

The above-mentioned difficulties of terrestrial observations are not the only reason for the late development of submillimeter astronomical research. A second, equally important, reason is the great complexity of the generation and detection of waves in this range. Submillimeter waves are "too short" for the methods developed in the centimeter and millimeter ranges. For example, the design of electronic generators of the return-wave type for this range requires the overcoming of great difficulties.[2] The superheterodyne approach is also extremely complicated in the submillimeter range,[3] and suitable low-noise high-frequency amplifiers of the maser or parametric-amplifier type have not yet been developed, being faced with difficulties other than merely technical ones.

On the other hand, the submillimeter waves are "too long" for the technology used in the infrared region. Thermal radiation sources give very low intensities in this range. There are great intrinsic difficulties in the development of coherent generators of the type of ir lasers. Receivers for the radiation must be cooled to very low temperatures. There are also great difficulties in the guiding of submillimeter waves.

Despite all these difficulties, the extension of astronomical research into the region of submillimeter waves is a very attractive field. It is known from experience in radio astronomy that observation of the cosmos through a new "window" can yield many unexpected things. The striking successes of radio astronomy lead us to think that great "surprises" must also be hiding in this adjacent and practically untouched submillimeter range. Besides this general assertion, however, we can already formulate a number of problems which make it reasonable to strive to overcome the many difficulties we have mentioned. Let us give our attention briefly to some urgent problems of submillimeter astronomy.

II. SOME PROBLEMS OF SUBMILLIMETER ASTRONOMY

Generally speaking, it is always interesting to study any type of cosmic objects in a new range of wavelengths. If we approach the matter from the side of shorter waves, in the visible and infrared, it is natural to expect that in the submillimeter range we shall obtain very interesting information about comparatively cold objects, for which the maximum of the equilibrium radiation lies in this range. On the other hand, this region can be of interest for spectral studies of objects for which the characteristic spectral lines or bands fall in the submillimeter range of wavelengths. The problems discussed below involve the need for such investigations.

1. The Study of the Characteristics of the Primeval State of Matter

On the basis of the expanding-universe theory, A. A. Friedmann predicted the possibility of the existence of an isotropic electro-magnetic thermal radiation corresponding to a black body temperature of a few degrees Kelvin. According to the hot model developed in the framework of this theory by a number of authors,[4] in an early stage of the expansion of the Universe the matter is characterized by a large entropy. In thermal equilibrium the density of the strong

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* Report at a session of the General Physics and Astronomy Section of the U.S.S.R. Academy of Sciences, November 13, 1968.

radiation in the compressed hot plasma exceeds the density of the matter by a large factor. In the process of expansion the number of quanta of the radiation is conserved, but their energies decrease as the wavelength increases owing to the red shift. At present, as shown for example in calculations by Doroshkevich and Novikov,[5] the density of this radiation, corresponding to black-body radiation at a few degrees Kelvin, is many orders of magnitude larger than the radiation density of other sources (radio galaxies and stars) in the range of wavelengths where the maximum of the radiation is to be expected.

At first the search for a cosmic radiation of the nature of this isotropic background was unsuccessful.[6] But careful measurements[7] being made at the same time (1965) for entirely different purposes, on the intrinsic noise of a sensitive receiving system consisting of a large parabolic-horn antenna and a low-noise amplifier tuned to wavelength 7.35 cm, led to the discovery of a cosmic background radiation, independent of the position of the antenna, and with an intensity corresponding to black-body radiation at temperature 3.5°K.

Immediately thereafter, in 1966–1968, various groups of observers in the U.S.A., England, and the U.S.S.R. made measurements of the background radiation at a number of wavelengths in the decimeter,[8,9] centimeter,[10-12] and millimeter[13-16] ranges, and all of the results agreed within the limits of measurement error with the black-body radiation curve for a temperature close to 3°K. It must be noted that only the shortest-wavelength (3.3 mm) measurements[16] of this series give an indication of the deviation of the Planck curve from the Rayleigh-Jeans law ($I_\nu \approx 2kT/\lambda^2$) toward the Wien part of the curve, providing evidence that the observed radiation is indeed black-body radiation at a thermodynamic temperature ~3°K, and not radiation from hotter, but "gray" (semitransparent), matter.† As can easily be seen from Fig. 1, which shows all of the results of radiometric measurements obtained up to 1969, the maximum of the Planck curve, corresponding to a temperature ~3°K, is close to $\lambda = 1$ mm, and its most interesting Wien section lies mainly in the submillimeter range of wavelengths. Careful spectral measurements in this range should not only give a definite answer to the question as to the nature of the background radiation, but also throw light on a number of fundamental cosmological problems.

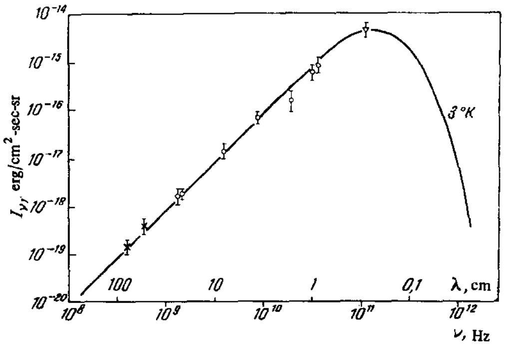

FIG. 1. Results of measurements of the cosmic background radiation, as given in [7-16].

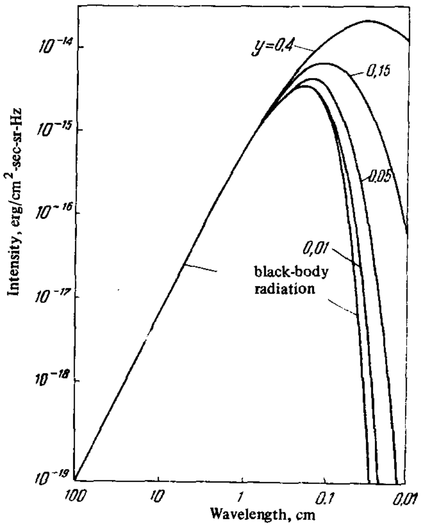

FIG. 2. Residual-radiation spectrum as affected by Compton scattering, according to the calculations in [22], for various values of the small parameter y that characterizes the distortion of the Planck spectrum.

A theoretical treatment[20-22] shows that the interaction of black-body radiation with matter at a definite stage of the evolution of the Universe must lead to distortions of the Planck spectrum of the residual radiation. In the hot model of the Universe it is assumed that at an early stage of the expansion a completely ionized hydrogen plasma was in equilibrium with the radiation. Later the cooling of the plasma with continuing expansion led to recombination of the hydrogen. It is shown in[21,22] that this process is acompanied by a distortion of the spectrum of the residual radiation in its short-wave or Wien branch; two-quantum decays of 2s levels of hydrogen atoms, occurring in the recombination, involve the emission of energetic quanta which raise the intensity of the background radiation in the Wien part of the curve. Though not very large, this rise becomes appreciable for $\lambda < 200\ \mu$. Measurements of the spectrum in this region can give information about the stage in which the hydrogen plasma recombined, which is believed to be in the period for which the red shift is $z \sim 10^3$. Such measurements may possibly allow an estimate of a very important quantity, the density of matter in the Universe, since the intensity of the recombination radiation essentially depends on this quantity.[22]

A distortion of the residual-radiation spectrum is also to be expected for another reason. At a later stage of the evolution, according to theoretical ideas,[20,22] a second heating up and ionization of the intergalactic gas must occur. A particular result of this is that scattering of the photons of the residual radiation by fast thermal electrons of the hot gas leads through the inverse Compton effect to an increase of the frequencies of the scattered quanta. Figure 2 shows

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*Later this value was corrected to 3.1° ± 1°K

†We cannot consider here various alternative hypotheses about the origin of the background radiation, for example [17]. This question has been considered in [18], for example; see also [19].

residual-radiation spectra calculated in[22] as affected by this effect, for various values of a dimensionless small parameter y, which characterizes the degree of interaction of the radiation and the electrons. We see that because of the scattering the maximum of the spectral density of the residual radiation is shifted toward shorter wavelengths, and the height of the maximum is larger than for the pure Planck spectrum. Measurements of the effect in the Rayleigh-Jeans region cannot give the answer to the question about an interaction with hot intergalactic gas, because here the intensity of the additional radiation is small in comparison with the background contribution of radio galaxies. Only measurements in the submillimeter range can give the answer.

It must be noted that besides direct radiometric measurements of the background radiation, for a number of waves in the millimeter and submillimeter ranges it has been possible to get estimates of the background radiation intensity by using the results of measurements of the relative intensities of absorption lines in the spectra of certain stars, caused by absorption in the molecules of interstellar CN, and also CH.[23,24] The main idea of the method is as follows. Molecules in interstellar space (of CN, CH, and so on) make practically no collisions with each other. Therefore transitions of molecules from a lower state of energy A to an excited state of energy A* occur only owing to interactions with radiation which is absorbed by a molecule when $h\nu + A = A^*$. Then the relative populations of the energy levels of the molecules are in the ratio $[A^*]/[A] = \exp(-h\nu/kT)$, where T is the effective temperature of the radiation in question. In particular, if the level difference $A^* - A$ corresponds to the quantum energy of millimeter or submillimeter cosmic electro-magnetic radiation, and independent measurement of the relative populations of these levels allows us to determine the effective temperature of the radiation for the corresponding wavelengths.

It is possible to measure the quantity $[A^*]/[A]$ by analyzing the relative intensities of related lines in the optical spectrum of a star, namely lines for which the states A and A* are the initial states.

The difference of the intensities of the closely spaced lines λ 3874.00 and λ 3874.61 Å, caused by absorption in CN molecules, as observed in the light of the stars ξ Persei and ξ Ophiuchi, are smaller than would be expected, which indicates a larger population than expected in the excited level and enables us to estimate the effective temperature of the background radiation at wavelength 2.63 mm. Analogous estimates for wavelengths 1.32, 0.559, and 0.359 mm have been obtained from analysis of measurements of absorption lines of CN, CH, and CH^+. These estimates (although rather rough) agree with the idea of a Planck radiation at a temperature close to 3°K. We shall return later to some of these measurements.

We were speaking earlier about measurements of the spectral intensity density of the residual radiation, whose distribution over the celestial sphere is nearly uniform according to the first observations. The very fact that the brightness temperature of the residual radiation is constant over the entire sky indicates that it is indeed residual in nature. But of necessity the first observations were not very exact, and could not cover large regions. Meanwhile a detailed study of the distribution of the brightness temperature of the background is of great interest. The discovery of an anisotropy—a dependence of the intensity of the background radiation on the angular coordinates—would be evidence for the correctness of an anisotropic cosmological model, and the nature of the dependence (quadrupole anisotropy or anisotropy of a more complex type) would permit a choice between different anisotropic cosmological models.[25,26] of equal importance are measurements of small-scale fluctuations (or perturbations) of the intensity distribution of the background radiation, which carry information about disturbances in the density of matter which have occurred at early stages of the evolution of the Universe.[27,28]

The limited attempts made so far to find anisotropy and irregularities in the distribution of the brightness temperature of the residual radio emission in the centimeter[29,30] and millimeter[31] ranges have met with no success, and have provided only an upper limit on the fractional changes of the brightness temperature of the background, in terms of the errors of the measurements and the fluctuations of the intensities of unresolved discrete sources ($\Delta T/T \lesssim 10^{-3}$ on the scale of regions with diameter $> 3'$). The continuation of such measurements with accuracy better than 0.1 per cent, and the possibility of resolving regions of diameter 1′ to 2′, is an extremely interesting but very complicated problem.

As can be seen from the foregoing, the detection, and, going beyond this, the detailed study of the low-temperature cosmic radiation in the submillimeter region calls for a careful consideration of all of the "parasitic" radiations, in particular the "glares" of low-temperature radiation from the atmosphere and from surfaces surrounding the sensitive element of the radiometer. Owing to this, precision measurements of the background radiation in the submillimeter range require not only that the apparatus be carried up beyond the limits of the atmosphere, but also cryogenic cooling of the antenna, the modulator, and the other elements of the radiometer that come before the cooled detecting element. Spectral measurements are extremely important for the solution of the problem in question. Observation of the total radiation in a wide spectral region is much less informative than spectrograms which show the relative changes of the spectral density of the radiation.

2. Investigation of the State and the Chemical and Isotopic Composition of the Intergalactic and Interstellar Media

The submillimeter range is a suitable place to study the extremely cold regions of the Galaxy. Measurements of the intensity distribution in this range would enable us to ascertain the regions where gravitational condensation may possibly be occurring at present; this is extremely important for stellar and planetary cosmology. In particular, the study of the spectrum of the submillimeter radiation will apparently enable us to discover the presence of various moleules and of dust in the Galaxy.

The maximum of the characteristic radiation of the interstellar dust can be expected at a wavelength of about 200 μ (on the assumption that the temperature of the dust particles is about 20°K). Furthermore it is known that a number of resonance lines of the rotational spectra of the molecules of hydrogen, oxygen, and some other gases are located in the millimeter and submillimeter ranges. The study of these lines would make it possible to study the colder condensed regions of the Galaxy—their temperature, density, and chemical composition.*

The submillimeter range also includes a number of lines of excited atomic hydrogen and other elements, corresponding to transitions between closely spaced energy levels with large quantum numbers (recombination radiation). The possibility of observing this radiation was first predicted, and it was first actually discovered, in the U.S.S.R.[33,34]

In 1968 the recombination line H56α was first observed (in the Omega nebula) in the millimeter range.[35] Measurements of the intensity, frequency, and width of recombination radiation lines are an effective means for studying the distribution, concentration, and electron temperature of regions of ionized interstellar gas, and also the velocities with which they are moving.

Although the brightness temperature of the recombination lines in the submillimeter range is smaller than at centimeter wavelengths, the spectral density of the radiation in a line must be much larger than the density of the thermal radiation of the galactic continuum in the same region of the spectrum. For the brightest nebulosities it is estimated that the expected fluxes from excited hydrogen lines in the range 0.5 to 1 mm (quantum numbers n = 10—50) are of the order of $3 \cdot 10^{-18}$—$3 \cdot 10^{-12}$ W/m², for a fractional width $\Delta\nu/\nu = 10^{-4}$.

3. The Study of "Infrared Stars" and Quasars

Hitherto unknown cosmic sources of electromagnetic radiation have recently been discovered. For example, there is a class of "infrared stars" which have the maxima of their spectra in the range 3—20 μ, which corresponds to the radiation of an absolutely black body at a temperature below 700°K. Very probably analogous objects will be discovered also at longer wavelengths, in the submillimeter range.

Observations indicate that the infrared and submillimeter ranges may contain the spectral maxima of the radiation of some powerful cosmic sources. The known radio source Taurus-A, which is remarkable in many ways, appears according to the latest measurements to be also a source of intense radiation in the submillimeter range. Figure 3 shows the spectrum of this source, as obtained from many observations by many people.[36] We at once note the sharp rise in the region of the submillimeter waves, where other observational data are so far completely lacking.

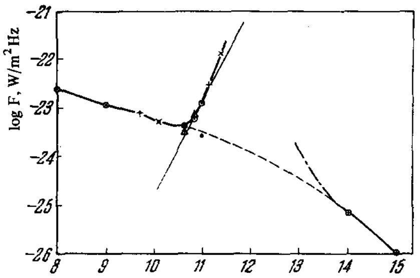

FIG. 3. Spectrum of the electromagnetic radiation of the sources Taurus A. ——— observed continuous radiation; – – – – the continuum without the excess in the submillimeter range; —·—·— the possible excess. The variously shaped points give the results of different observations (see [36]).

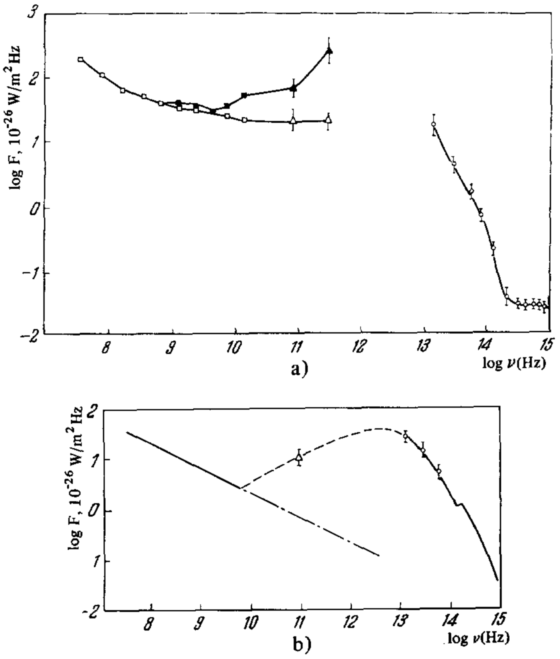

FIG. 4. Spectra of discrete sources: a) 3C273 (quasar), and b) NGC 1068 (Seifert galaxy), according to the data of [37] and [38]. □ are minimal and ■ are maximal fluxes between 1964 and 1967, according to the data of [37]. △ are minimal and ▲ are maximal fluxes according to the data of [38]. ○ are data from infrared and optical measurements.[38]

Quasistellar sources (quasars) have a wide variety of characteristics, in particular variable intensity and partial polarization, and their radio radiation in the millimeter and submillimeter ranges has unusual spectra. Figure 4, a shows the spectrum of the quasar 3C273, as obtained by combining the radioastronomical results given in[37] and the data from measurements in the infrared region presented in a review by Low.[38] The variability of the flux increases with decreasing wavelength, and the mean value of the flux in the submillimeter range is anomalously high. The mechanism for this increased radiation flux is not yet clear; it is assumed[38] that it is due to excess radiation from dust heated to hundreds of degrees by radiation coming from a central hot object.

Observations in the infrared region to 22 μ have also led to the discovery of intense radiation from several Seifert galaxies.[38] These sources also have

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*Recently it has been reported that emission resonance lines of ammonia (ν_1 = 23694.5 MHz and ν_2 = 23722.6 MHz) have been discovered in the direction toward the center of the Galaxy.[32]

peculiar spectra with maxima in the far infrared region. Figure 4, b shows the spectrum of such a galaxy, NGC 1068, as obtained from measurements[38] in the infrared and microwave regions. Apparently the source of the increased infrared radiation is the nucleus of the galaxy, but the mechanism of this radiation is not evident.

Calculations[39] show that the total radiation of sources with excess spectral density in the far infrared—the infrared galaxies—can give rise to a background radiation in the submillimeter range which is comparable in intensity with the residual radiation. Its spectrum adjoins the spectrum of this latter radiation on the shortwave side. Estimates indicate that the radiation from the infrared galaxies (which number perhaps one percent of all galaxies) makes a quite perceptible contribution to the total energy balance of the Universe, comparable with the radiation of all the other galaxies. Owing to this there is great interest in both direct observations of the background radiation at wavelengths about 100 μ over a wide field of view, and in surveys of particular sections of the sky by means of telescopes capable of resolving a large number of individual sources. Elucidation of the spectra of these objects will make it possible not only to understand the mechanism with which they radiate, but also to make a choice between various cosmological models.[39] Of course such observations are possible only by the use of very sensitive radiometers carried up beyond the limits of the atmosphere.

The expected fluxes from the brightest objects at wavelengths 500—100 μ should evidently be 10^{-24}—10^{-25} W/m^{2}Hz, which over a bandwidth $\Delta\nu/\nu = 30\%$ amounts to 10^{-12}—10^{-13} W/m^2.

4. Study of the Sun's Radiation

The submillimeter radiation of the Sun is a source of information about the deepest layers of the solar atmosphere.

For the submillimeter range the effective radiating layer is at a comparatively low temperature, probably less than 5000°K. Measurements in this range are extremely promising, since here the interpretation of the results of the measurements is greatly simplified. For the expected temperature we know that we can apply the Rayleigh-Jeans law in the submillimeter range (unlike, for example, the ultraviolet range), and we can easily go from the measured flux to the electron temperature.

On the other hand, it is precisely in the submillimeter range that data on the brightness temperature of the Sun have until very recently been entirely lacking (Fig. 5). It is especially interesting to get measurements in the submillimeter range on local sources on the Sun—their intensities, polarizations, motions—as functions of time. Obviously observations in this range will give much interesting material on the flashes associated with chromospheric flares, which play an extremely important part in many geophysical phenomena.

Spectral studies of the Sun in the submillimeter range are of especial interest.

Theoretical investigations[40,41] have shown that the effect of so-called dielectron recombination leads to a considerable over population of the high levels of multiply ionized atoms in the solar corona. This in turn can lead to the appearance of resonance absorption lines in the submillimeter spectrum of the Sun owing to transitions between neighboring levels, $n \rightarrow n-1$. According to estimates, for electron temperature and electron density in the corona $T_e = 10^{6}$°K and $N_e = 10^{8}$—10^{9} cm^{-3}, and for temperature $T \approx 6 \times 10^{3}$°K of the "black" photosphere, for the levels n for which the overpolulation is largest* we can expect at $z \approx 10$ an optical thickness $\tau \approx 10^{-2}$ in the absorption lines, i.e., a contrast of the order of 6°K. We must indeed note that the fractional width of these lines is $\Delta\nu/\nu \approx 10^{-4}$. Accordingly very high resolution is needed for their detection. A smaller resolution will suffice, however, to find regions of the spectrum in which the lines of particular elements are grouped.

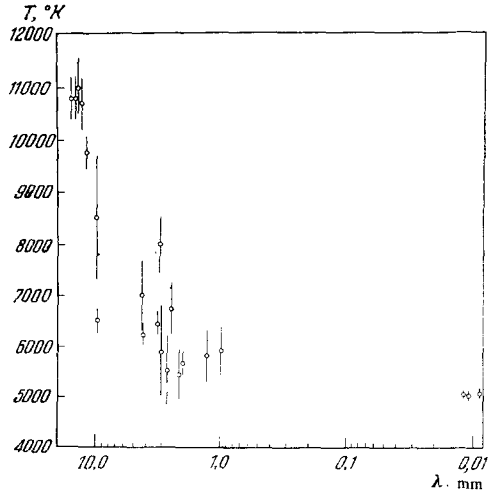

FIG. 5. Results of measurements of the brightness temperature of the solar disk in the radio and infrared ranges. There is a striking lack of data in the submillimeter range.

5. Research on the Planets

The submillimeter region is also of undoubtd interest for the study of physical conditions on the Moon and on the planets of the solar system. As measurements of the intensity of infrared radiation provides information about the surface temperatures of the Moon and the planets, similar measurements in longer ranges of wavelengths—the submillimeter and the millimeter ranges—offer a possibility of learning about the temperature and properties of the layer just below the surface. The first measurements of this kind, though made under unfavorable terrestrial conditions, show the promise of submillimeter lunar and planetary measurements. Of even greater interest are submillimeter radiometric measurements of planetary atmospheres, which can provide information about the layers in an atmosphere which are transparent for longer wavelengths. Submillimeter spectral measurements will be of particular interest.

As is well known, the millimeter and submillimeter

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*At wavelengths $\lambda \approx 1$ mm we have for this n = 60.

ranges contain many bands of rotational transitions of the molecules of gases whose presence is assumed or has been demonstrated in planetary atmospheres. Molecular submillimeter astrospectroscopy is still in the embryonic stage, but in principle it is extremely promising.

We can illustrate the situation that exists here with the example of the Earth's atmosphere. Figure 6 shows the absorption spectrum of the water vapor of the Earth's troposphere, calculated for sea level.[42] The density and temperature fall off with height, and the widths and intensities of the lines decrease, so that from the changes of the spectrum with height one can get evidence on the abundances of components of the atmosphere and on the temperatures of its layers. As an example Fig. 7 shows absorption spectra of the Earth's atmosphere in the submillimeter range, calculated for heights of 0.5, 3.5, and 30 km above sea level.[43]

These same figures illustrate the difficulties of terrestrial observations, which were mentioned earlier. Submillimeter research, especially at wavelengths shorter than 1 mm, is for the most part possible only outside the atmosphere, where the water vapor does not affect the measurements.

III. METHODS OF EXTRA-ATMOSPHERIC SUBMILLIMETER ASTRONOMY

Before discussing the methods of extra-atmospheric measurements, let us look briefly at the state of submillimeter detection technique.

Many reviews, in particular the well known one by Putley,[4] give overdetailed lists of possible ways to detect submillimeter radiation. The present state of experimental technique for submillimeter waves, in particular the methods for detection and spectral analysis of the radiation, is expounded in detail in[3], and also in the review[45].

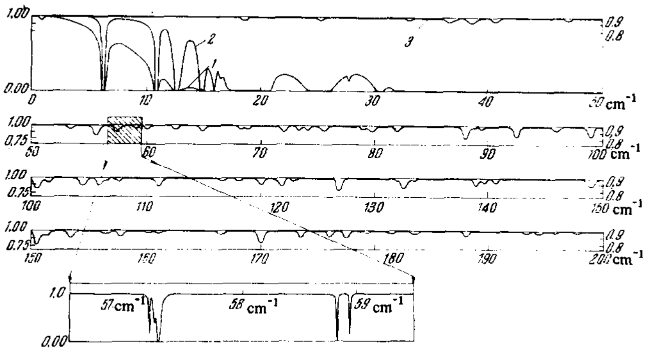


FIG. 7. Changes of the absorption spectrum in the Earth's atmosphere with height, according to the data of [43]. 1 is for 0.5 km above sea level; 2 is for 3.5 km above sea level; and 3 is for 30 km above sea level (the last case shows the convolution of the transparence curve and an apparatus function of width 0.5 cm^{-1}). The actual transparency curve is shown below for 57–59 cm^{-1}.

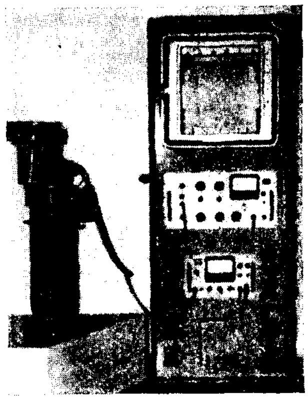


FIG. 8. Submillimeter radiometer with indium antimonide detector, developed at the Institute of Radiotechnology and Electronics of the U.S.S.R. Academy of Sciences [50,51,63].

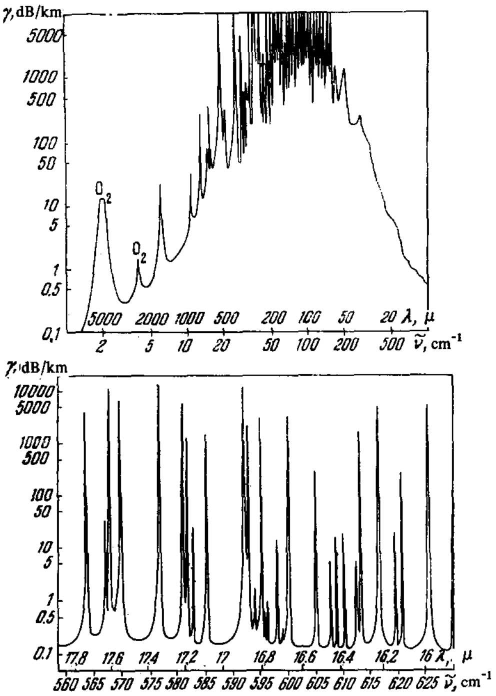


FIG. 6. Absorption spectrum of the water vapor in the Earth's atmosphere at sea level (T = 293°K, p = 760 mm Hg, ρ = 7.5 g/mm^2), as calculated in [42].

For the long-wave part of the range there have now been developed and used radiometers with ultrabroadband detecting[46] and superheterodyne[47] receivers with crystal mixers at the input (for wave-lengths right down to 0.5 mm). "Optical" methods are represented by optical-acoustical converters, and by various types of bolometers, including superconducting germanium bolometers cooled to helium temperatures. Evidently the most promising of the receivers that have been developed are bolometers and photoresistive detectors with semiconducting elements of germanium and indium antimonide. The table shows the parameters of some detectors now being used:

Radiometers with these types of detectors have been developed and used for terrestrial measurements in England, the U.S.S.R., the U.S.A., and France.[48-52] As an example, we show in Fig. 8 a submillimeter radiometer with an indium antimonide detector[53] developed in the Institute of Radiotechnology and Electronics of the U.S.S.R. Academy of Sciences[50,51,63].

Advances in the field of quantum electronics, in particular the development of gas lasers in the submillimeter range[45] and attempts at heterodyning with cooled nonlinear semiconducting elements,[54] provide

Type of receiver	Working temperature, °K	Minimum detectable power ΔP_{min}, W (for τ = 1 sec)	Time constant of detector, τ, sec	$\sqrt{\overline{\delta T^2}}$ ($\lambda = 0.5$ mm)	Frequency band Δf, MHz
Superheterodyne with crystal detector	300	$1.1 \cdot 10^{-13}$	10^{-9}	130	60
The same	300	$1.7 \cdot 10^{-13}$	10^{-9}	10	1200
Optical-acoustical converter	300	$3 \cdot 10^{-10}$	0.015	$4.5 \cdot 10^{-1}$	$6 \cdot 10^4$
Carbon bolometer	2.1	$1 \cdot 10^{-11}$	0.01	$1.5 \cdot 10^{-2}$	$6 \cdot 10^4$
Germanium bolometer	2.15	$5 \cdot 10^{-13}$	$4 \cdot 10^{-4}$	$7.5 \cdot 10^{-4}$	$6 \cdot 10^4$
Superconducting bolometer	3.7	$3 \cdot 10^{-12}$	1.25	$4.5 \cdot 10^{-3}$	$6 \cdot 10^4$
Broad-band indium antimonide detector with magnetic field	1.5	$1 \cdot 10^{-11}$	$2 \cdot 10^{-7}$	$1.5 \cdot 10^{-2}$	$6 \cdot 10^4$
Indium antimonide detector without magnetic field	4.0	10^{-12}	$3 \cdot 10^{-7}$	$1.5 \cdot 10^{-3}$	$6 \cdot 10^4$

$$\sqrt{\overline{\delta T^2}} = \frac{\lambda^2 \Delta P_{min}}{2k\,\Delta f} \quad [\text{deg-sr-cm}^2]$$

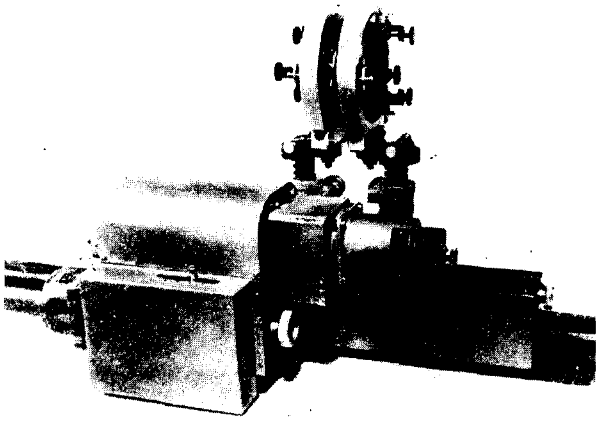


FIG. 9. Submillimeter Fabry-Perot interferometer using fine-wire mirror, developed in the Lebedev Physical Institute of the U.S.S.R. Academy of Sciences.

hope for the successful development of efficient superheterodyne radiometers with a low noise level.

We should note the considerable advances in the fields of guiding, filtering, and measuring submillimeter waves, and in particular in polarization and interference measurements. Figure 9 shows a submillimeter Fabry-Perot interferometer developed in the Lebedev Physical Institute of the U.S.S.R. Academy of Sciences,[55,56] in which the mirrors consist of plane one-direction meshes of thin metal wires of diameter d, stretched parallel to each other at interval l on rings of diameter a, the condition $a \gg \lambda > l > d$ being satisfied. For radiation polarized parallel to the wires a mirror made in this way has an extremely high reflection coefficient $R_{\parallel} \gtrsim 0.99$ and small losses.

Figure 10 shows a submillimeter Fourier spectrometer developed at the National Physical Laboratory (England).[57]

Unlike radiometers for the microwave range, in which single-mode radiation detectors are used, instruments for the submillimeter range mainly use detectors whose linear dimensions are larger than the wavelength of the radiation in question. Each element of such a detector converts the radiation falling on it, independent of the rest. This circumstance leads, as is well known, to changes in the formulas for the directivity of the receiver and for the fluctuation threshold of its sensitivity.[52,58,59]

A serious problem is that of developing standard sources in the submillimeter range, which are necessary for the calibration of the radiometers, especially in the low-temperature region. There are great difficulties, which have not yet been overcome, in developing nonmechanical modulators analogous to those used in the microwave range.

The main problems in developing the technology of extra-atmospheric submillimeter astronomy arise from the necessity of carrying the receiving apparatus beyond the limits of the atmosphere, or at least partially eliminating its effects.

Naturally the simplest method is to take the radiometers to mountain tops, where for the most part the humidity is less than 1 g/m^3.

The most promising approach, however, is to use for submillimeter astronomical research the methods of extra-atmospheric astronomy. A relatively simple method is to send the apparatus up in airplanes and stratospheric balloons. The first published results from the use of airplanes and balloons for measurements in the submillimeter range are extremely promising. The results of attempts to measure the water-vapor spectrum at a height of about 12 km in the range 15–65 cm^{-1} (600–150 μ)[57] are shown in Fig. 11. The measurements were made with the submillimeter Fourier spectrometer mentioned above.

Balloon techniques have been widely used recently in infrared astronomy. There are apparently no difficulties in principle in extending these methods to the submillimeter range. But the severe requirements on the sensitivity of the radiometers makes it necessary to develop cryostatically cooled detectors which can be sent up with balloons. Of course there is always the difficulty of orienting the optical systems.

The first attempts in this direction were made in the U.S.A.[61] The gondola of a stratospheric balloon which went up to 30 km contained a modulation radiometer with a detector which consisted of a germanium

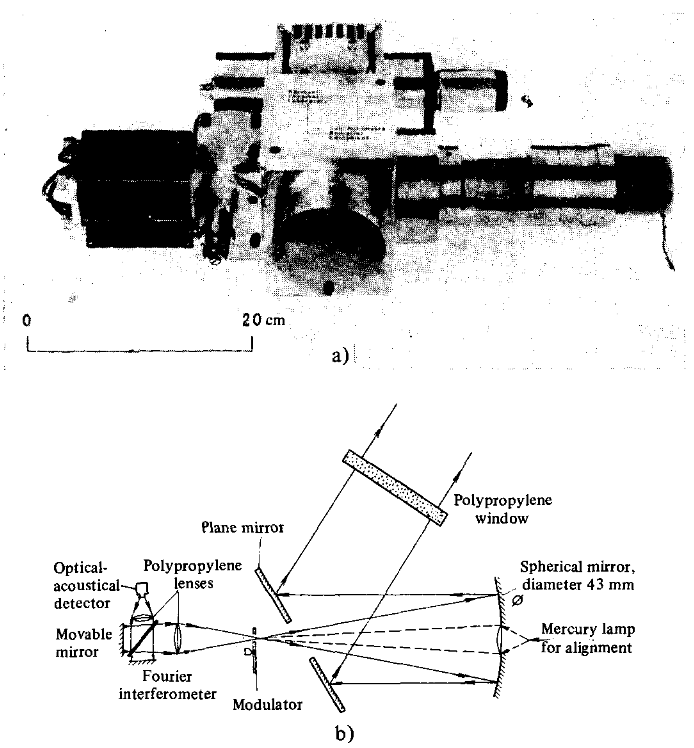


FIG. 10. Submillimeter Fourier spectrometer developed at the National Physical Laboratory (England).[57]

bolometer cooled with liquid helium. The sensitivity achieved at temperature 1.8°K was 7×10^{-14} W/sec$^{1/2}$. An interesting peculiarity of the apparatus was the use of an outside vacuum for pumping the helium flask. Measurements were made over the wavelength range 300–450 μ with maximum at 320 μ. The modulation was produced by rocking a reflecting mirror, and therefore the radiometer determined only the gradient of the intensity of the radiation observed. No sources other than the Moon were found (Fig. 12). The upper limit on the increase of the radiation flux over background in the range 300–360 μ from a region of 10^{-3} sr was 2×10^{-23} W/cm^{2}Hz, so that the results showed that there were no discrete broad optical sources of diameter $\gtrsim 2°$ and temperature $> 10°$K.

It is important that this experiment did not reveal any radiation sources of atmospheric origin, which could present obstacles to stratospheric submillimeter astronomical measurements.

Also of great interest is research in the field of extra-atmospheric submillimeter astronomy begun about two years ago at the Medon Observatory (France).[62] Using the hydrogen balloons of the French National Center of Cosmic Research, with gondola stabilized to accuracy 10–20″ with reference to the Sun or a bright star, the Medon group investigated the Sun's spectrum with resolution 0.3 cm^{-1} over the range 50–2300 μ. The last flight, at the beginning of 1968, was successful; the Sun's spectrum was registered, and attempts were made to use it to estimate the brightness temperature. Figure 13 shows a model of the stratospheric radiometric apparatus of the Medon observatory.

Stratospheric experiments in the submillimeter range with the use of an indium antimonide detector cooled to liquid-helium temperature were first made

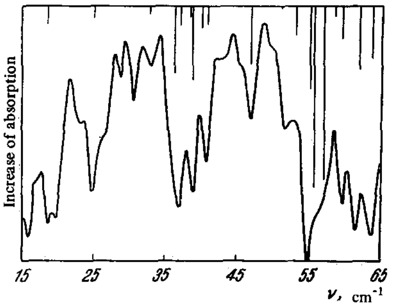


FIG. 11. Submillimeter absorption spectrum of the Earth's atmosphere, measured at a height of 12 km.[57]

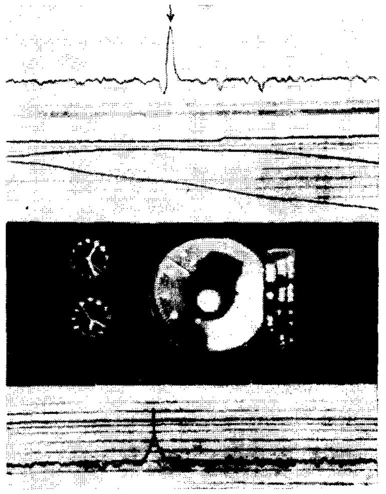


FIG. 12. Record of the radio radiation of the Moon in the range 300–450 μ, obtained with a stratospheric balloon at height 30 km.[61]

in the Soviet Union in the summer of 1968 in the Lebedev Physical Institute of the Academy of Sciences of the U.S.S.R.[63] Figure 14 shows a block diagram of the flyable radiometer developed at the Institute. A vertical scan with aperture 5°, and also azimuthal surveys, were made in two flights at altitude 35 km. One of the curves of the distribution of brightness temperature of the Earth's atmosphere in a vertical plane is shown in Fig. 15.

The above-mentioned difficulties of extra-atmospheric observations are greatly increased when one tries to use rockets or artifical satellites for the observations.

There are two problems to be solved, and progress with them will evidently determine the rate of development of submillimeter astronomy. They are: a) the development of submillimeter-wave mirror antennas equipped with appropriate tracking mechanisms, and b) the use in satellites of detecting devices cooled to liquid-helium temperatures.

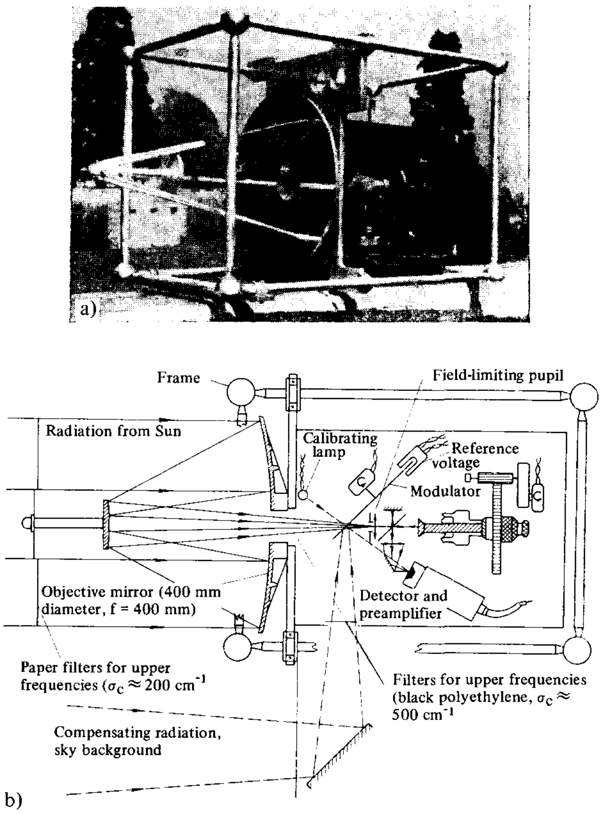


FIG. 13. Model of the stratospheric radiometric apparatus of the Medon Observatory. a) General view of apparatus; b) block diagram of radiometer.[62]

As for the antennas, here it would seem that the problems may be in some respects rather less difficult than under the conditions of astronomy on the Earth's surface.

The absence of wind and weight loads partly simplifies the engineering calculations. The main problems are those of assembly and reliable aiming of the sharply-directional antenna of the submillimeter telescope toward the object of an observation, together with the problem of avoiding thermal distortions of the mirror, which for observations on discrete sources of radiation should preferably have dimensions as large as 10 to 20 meters.

The problem of cooling the detector of a rocket or satellite apparatus is rather complicated. The requirement of cooling to 4.2°K (if there is no development of semiconducting or other sensitive elements whose operation does not require such a low temperature) means that a space filled with liquid helium must be provided. Maintaining this requires either operation of an economical small-scale closed-cycle cryogenic system or the development of a cryostat which can keep liquid helium for a long time.

In this connection the results of methodological experiments done at the Lebedev Physical Institute are of interest.[64,65] In these experiments various methods for maintaining temperatures below 10°K in artificial satellites were tested.

In the first experiment[64] the cooling agent was helium in a "supercritical" state, at pressure 2.4 atm (the initial temperature was about 5.2°K). During the flight regular measurements were made of the temperature at six points in the helium container, the pressure in the container, and the magnetic field strengths in two superconducting solenoids. Measurements made with the sputnik "Cosmos-140" showed that under the conditions of orbital flight, in the state of weightlessness, this system for maintaining the low temperature necessary for operation of superconducting systems can be successfully operated.

The second experiment[65] tested the possibility of keeping liquid helium in a cryostat in an artificial satellite. A metal cryostat with nominal volume of the helium bath 1.3 liters, and without auxiliary nitrogen cooling, was installed in an artificial satellite.

Release of the evaporated gas occurred through a special valve which maintained a pressure of about 1.45 atm in the cryostat, which corresponds to temperature 4.6°K of the liquid helium. The temperature inside the helium volume was measured during the flight.

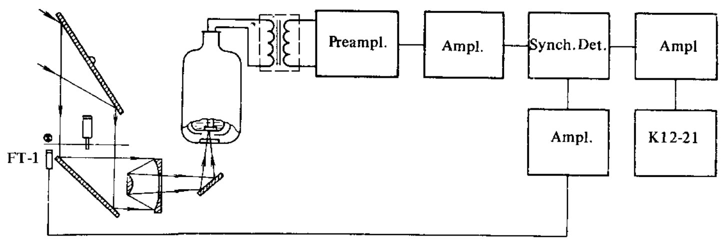


FIG. 14. Stratospheric submillimeter radiometer (Physical Institute, U.S.S.R. Academy of Sciences.) [63]

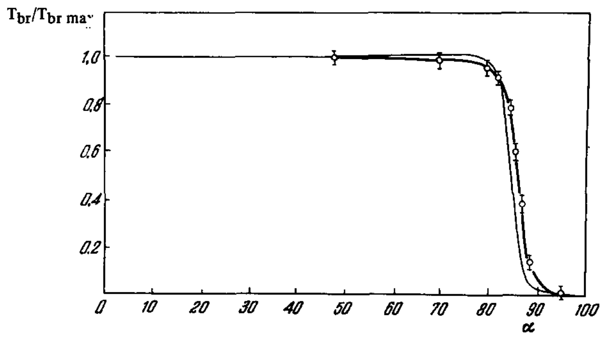


FIG. 15. Curve of distribution of brightness temperature of the radiation of the Earth's atmosphere, $T_{br}/T_{br\ max}$, in a vertical plane, obtained at altitude 35 km.[63] α is the angle between the optical axis of the radiometer and the nadir. Random errors (rms) of the measurements are indicated. Average of 15 records between 10^h44^m and 11^h27^m. Heavy curve drawn through observed points; light curve is calculated from an atmospheric model.

The results of the experiment confirmed the effectiveness of this type of cryostat under conditions of weightlessness, overloads, and vibration. The time for which the liquid helium was preserved was close to the calculated value (about 24 hours).

A preliminary communication about the first experiment made in the U.S.A. in the submillimeter range with a geophysical rocket was published in November, 1968.[66] On February 29, 1968, an "Aerobee" rocket was used to lift a small reflecting telescope of diameter 170 mm, entirely cooled to liquid-helium temperature. The wavelength range from 5 μ to 1.3 mm was covered by means of four semiconducting detectors, including an indium antimonide detector for the range from 0.4 to 1.3 mm. The long-wavelength limit of the measured spectrum was set by means of a grid filter. The field of view of the Cassegrain telescope was 5°. The detectors were placed in the focal plane of the mirror in a cavity with an opening. The radiation entering the cavity was modulated with a tuning-fork modulator at frequency 150 Hz.

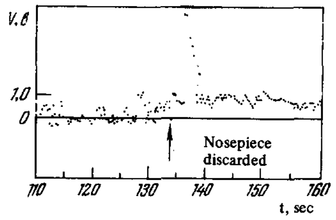
Before startup and during the active part of the flight the upper part of the telescope was covered with a shutter cooled to a very low temperature. During this time the detector registered only the radiation from the inside walls of the cooled telescope. At altitude 130 km, after the nosepiece of the rocket had been jettisoned, the entrance aperture of the telescope was opened, and at this point a marked increase of the signal in the submillimeter channel was registered (Fig. 16). In accordance with calibrations made before the flight, the increase of the signal was interpreted by the authors as the result of the appearance of a radiant flux of 5×10^{-9} W/cm^2 sr in the range 0.4—1.3 mm (with a possible error of about a factor two).

If we ascribe this flux to cosmic background radiation, its brightness temperature must be $8.3^{+2.2}_{-1.3}$°K. The measured cosmic radiation flux is almost two orders of magnitude larger than would be expected if the brightness temperature of the background radiation is close to 3°K.

The authors of the communication give a number of arguments to exclude other possible causes of this strong rise of the signal. In particular, the possible glare of radiation coming from thermal sources of local origin or from the Earth can evidently be excluded, since the detectors that registered the radiation in the infrared range did not show an increase of signal when the shield was opened. On the other hand, it is worth notice that the increase of the signal (see Fig. 16) possibly occurred a bit before the discarding of the nosepiece (its radiation in the field of view of the telescope is registered as a peak). Also the measurement procedure is not quite irreproachable; the opening of the cover can scarcely have failed to affect the conditions of radiative transfer inside the telescope.

It must be emphasized that the large flux density of cosmic background radiation found in this experiment is in serious contradiction with the entire collection of data obtained earlier. Also, since the publication of the results of the rocket experiment,[66] an additional and more careful measurement of the upper limit of the cosmic flux of radiation has been made[60] by the previously mentioned method of comparing the intensities of closely adjacent lines of the absorption spectra of the molecules CN, CH, and CH⁺. These measurements showed that the brightness temperature of the background radiation at wavelength λ = 2.64 mm is 2.83°K to within an accuracy of 0.15°K. The brightness temperatures obtained from measurements with CN, CH, and CH⁺ molecules at the respective wavelengths 1.32, 0.559, and 0.359 mm cannot exceed the values 4.74, 5.21, and 8.11°K. The corresponding upper-limit values for the radiant flux at these wavelengths are 1.92×10^{-14}, 1.64×10^{-14}, and 6.19×10^{-14} erg cm^{-2}

FIG. 16. Telemetric record of the change of the signal at the output of the logarithmic amplifier of the submillimeter channel (0.4—1.3 mm) before and after discarding the nosepiece of the rocket (the time of the discarding is indicated by an arrow), according to the data of [66].



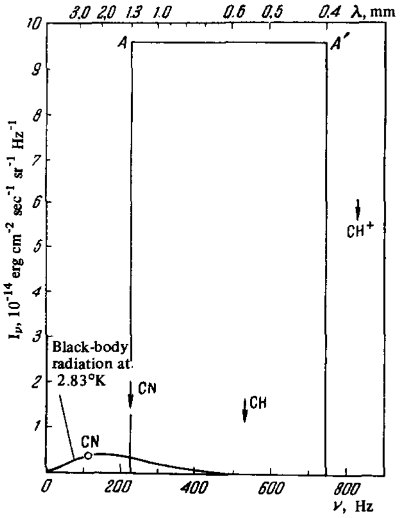


FIG. 17. Intensity of cosmic submillimeter radiation according to data on comparative measurements of absorption lines [60] and from a rocket experiment [66] (line AA′).

$\sec^{-1}\mathrm{sr}^{-1}\mathrm{Hz}^{-1}$. For wavelength $\lambda = 2.64$ mm the corresponding flux density is 0.37×10^{-14} erg $\mathrm{cm}^{-2}\sec^{-1}\mathrm{sr}^{-1}\mathrm{Hz}^{-1}$.

Figure 17 shows the flux values obtained from the analysis of line intensities and from the rocket experiment (line AA′). The sharp contradiction between the results is obvious. Accordingly, the first measurement of the background radiation in the submillimeter range made by a method of extra-atmospheric astronomy has not only made the situation clearer, but has complicated it still more. This should not be surprising, however. In demonstrating the complexity of extra-atmospheric research, this is to be regarded as a pioneering experiment, which will undoubtedly be followed by others.

Advances in the technology of extra-atmospheric submillimeter experiments will bring nearer the time when submillimeter astronomy can make a serious contribution to our understanding of the cosmos.

Note added in proof. During the time since this article was written new publications bearing on its subject have appeared. A number of papers have given improved or completely new formulations of astrophysical problems which call for measurements in the submillimeter range.[67–77] Others [78–80] describe research on the absorption of submillimeter radiation in the Earth's atmosphere, and deal [81–85] with problems of the apparatus of submillimeter astronomy. The results of measurements of the cosmic flux of submillimeter radiation [65] in the range 0.4–1.3 mm have been supplemented by the publication of the results of a repetition of this experiment, [86] and also there are additional data [87] confirming the existence of an anomalously large radiant flux in this region. Intense radiation from the center of the Galaxy has also been found at ~ 100μ [88] and 5–1500μ.[89] Unexpectedly intense radiation from Jupiter and Saturn has been registered by apparatus carried in an airplane.[90]

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