SOME PROBLEMS AND INSTRUMENTAL FEATURES OF SUBMILLIMETER ASTRONOMY

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1. Introduction

Modern astronomy includes optical, ultraviolet, infrared and, in recent years, radio, γ-ray, and X-ray astronomy. Such a classification is justified to a certain degree. In fact, the difference in wavelength ranges causes a distinction in the methods and techniques of receiving radiation. Also, the solution of specific problems requires observation in different wavelength regions. In this respect it is possible to describe a new astronomical branch, the submillimeter one.

The submillimeter range is intermediate between the infrared and microwave regions, as shown in Table 1. The boundaries of this region are not very definite. Some authors include in the submillimeter range the wavelengths longer than 50 microns, others, those longer than 100 microns. The long wavelength edge of the range is also diffuse. Formally it is a wavelength of 1 mm, but in some cases the 2-mm or 4-mm wavelengths are also included in the submillimeter range. The measurements of submillimeter receiver performances are sometimes carried out at wavelengths up to 8 mm. The uncertainty of the boundaries is very understandable: their shifting depends on the methods of generation, transmission, and detection of radiation. In this review paper, following Martin's (1962, 1963) terminology, wavelengths between 50 microns and 2 mm will be attributed to the submillimeter range.

Among other branches of astronomy, submillimeter astronomy may perhaps most reasonably claim to go beyond the Earth's atmosphere, since the Earth's atmosphere is practically opaque for space submillimeter radiation. Absorption by atmospheric water vapour prevents any serious astronomical observation from sea level.

In Figure 1 are shown the results of calculations of the absorption by atmospheric water vapour which have been performed byŽevakin and Naumov (1963). Even in the windows of relative transparency at wavelengths shorter than 2 mm, the absorption coefficient turned out to be more than 1 db/km. The results of these calculations are in satisfactory agreement with observational results in the millimeter (Straiton and Tolbert, 1960; Salomonovič, 1964; Wort, 1962; Drjagin *et al.*, 1966) and submillimeter (Drjagin *et al.*, 1966) wavelengths, as well as in the infrared region.

Submillimeter astronomy has appeared possible only in recent years and its development is due to two reasons: (1) the success in semi-conductor physics and quantum

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Table 1

λ mm	λ μm	ν GHz	ν cm^{-1}	Photon energy eV	Spectral range
10	10000	30	1	0·0001	
8	8000	37	1·23		Microwave
5	5000	60	2		(mm)
4	4000	75	2·5		
2	2000	150	5		
1	1000	300	10	0·001	
0·5	500	600	20		Far IR
0·2	200	1500	50		or sub mm
0·1	100	3000	100	0·01	
0·05	50	6000	200		
0·01	10	30000	1000	0·1	IR
0·001	1	300000	10000	1·0	

electronics; (2) the extremely rapid development of space-astronomy techniques which allow us to eliminate completely, or for the most part, the influence of absorption in the Earth's atmosphere. However, the progress of submillimeter astronomy could hardly be explained only by new technical possibilities. The main reason is that the solution of certain specific and important problems requires observations in just the range under consideration.

Before proceeding to the techniques involved, I would like to touch briefly on several points.

2. Some Problems of Submillimeter Astronomy

Until the present, the submillimeter window into space has been, and perhaps still is, strictly curtained (if not completely closed). Extension beyond the Earth's atmosphere promises extremely unusual discoveries. The first attempts at submillimeter observations confirm this statement. Even before the wide program of observations began to develop, the astrophysicists tried to formulate some problems which required submillimeter astronomical activity.

A. THE CHARACTERISTICS OF PRESTELLAR MATTER

The expanding universe theory of A. A. Friedman predicted the possible existence of an isotropic electromagnetic thermal radiation with a black-body temperature of several degrees Kelvin. In accordance with the model of a hot universe, developed in the framework of this theory by several authors (Zeldovič, 1966), matter in the prestellar state is specified by high level of entropy. In thermal equilibrium, the density of strong radiation in a compressed hot plasma at an early phase is many times greater than the density of matter. In the process of expansion the number of quanta remains the same but their energy diminishes, causing an increase in wavelength. The density

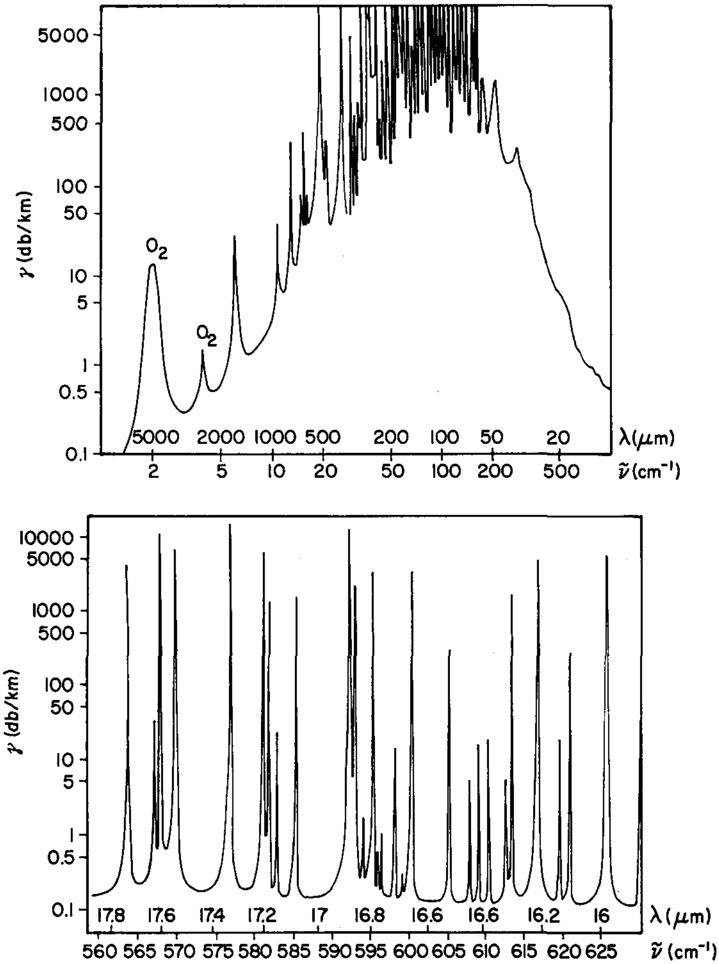

FIG. 1. *Absorption in atmospheric water vapour (db/km) calculated by Ževakin and Naumov (1963)* ($T = 293°K$, $P = 760$ mm Hg, $\rho = 7{\cdot}5$ gm^{-3}).

of this radiation at present was found to be many orders of magnitude greater than that of other sources of radiation (radio galaxies, radio stars) in the wavelength range where the maximum of the radiation curve occurs. Figure 2 shows the predicted spectrum calculated in 1964 by Novikov and Doroškevič for a proposed temperature of 1 °K.

Figure 3 shows some recent observational results. The measurements carried out by Penzias and Wilson (1965) at the wavelength $\lambda = 7{\cdot}3$ cm, and observations made by Rall and Wilkinson (1966) and Stankevič *et al.* (personal communication) at $\lambda = 3{\cdot}2$ cm, apparently suggest the existence of such radiation with an approximate blackbody temperature of ~3 °K. The same conclusion is supported by the analysis of the rela-

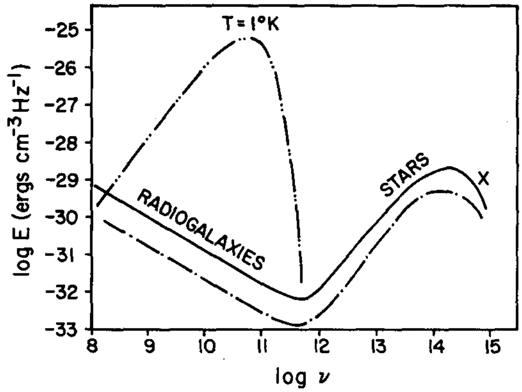

FIG. 2. *Spectrum of stellar and radio-source radiation together with background spectrum ($T = 1°K$) corresponding to the hot model (calculated by Doroškevič and Novikov, 1964, Doklady AN SSSR,* **154**, 745).

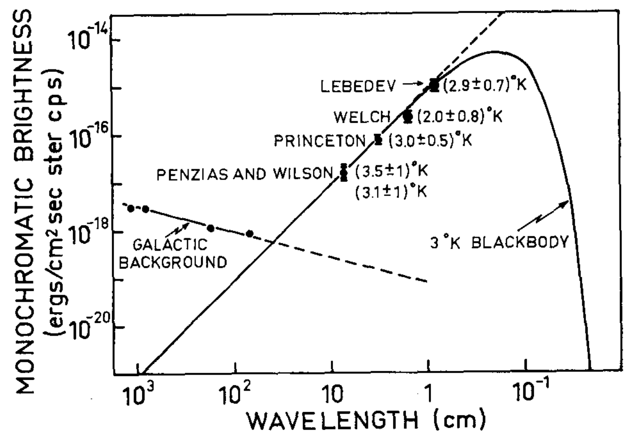

FIG. 3. *Planck's radiation for $T = 3°K$ and the recent results of background measurements in cm and mm regions (see Field and Hitchcock, 1966; Thaddeus and Clauser, 1966).*

tive intensity measurements of interstellar CN lines ($\lambda = 3874{\cdot}60$ Å and $\lambda = 3874{\cdot}61$Å) giving the temperature of background radiation at wavelength 2·53 mm (Field and Hitchcock, 1966; Thaddeus and Clauser, 1966). In July, 1967, V.S. Stankevič, V.I. Puzanov and the author of this paper (Puzanov *et al.*, 1967) completed an absolute measurement of the cosmic background radiation at a wavelength of 8·2 mm. The measurements were carried out with the help of a sensitive superheterodyne radiometer and artificial black-body screens cooled to liquid-nitrogen temperature. The black-body temperature of the background radiation turned out to be $2{\cdot}9 \pm 0{\cdot}7$ °K (root-mean-square error).

The maximum of the background radiation falls at a wavelength ~1 mm. After the discovery of this background radiation, it is very important to make measurements with the high accuracy at wavelengths shorter than 1 mm. These measurements apparently allow us to conclude whether the spectrum of the background radiation is a Planck distribution. Probable features of this spectrum may give some unique information about different stages of the evolution of the universe (Galaxy condensation, etc.).

B. STATE AND CHEMICAL COMPOSITION OF INTERSTELLAR AND INTERGALACTIC MATTER

Submillimeter wavelengths provide the optimum range for investigating the very cold parts of the Galaxy. Measurements of the intensity distribution in this range allow us to detect the regions where, perhaps, gravitational condensation is continuing, which is very important for theories of stellar and planetary cosmogony. In particular, detailed spectral investigation in the millimeter and submillimeter ranges should allow us to detect the existence of molecules and dust in the Galaxy. At wavelengths close to 20 μm one would expect to find the maximum radiation from interstellar dust, under the assumption that the dust temperature is close to 20 °K.

Further, it is known that several resonance lines of hydrogen, water, oxygen, and some other molecules occur in the millimeter and submillimeter ranges. The investigation of these lines permits the investigation of the temperature, density, and chemical composition of the coldest and most condensed parts of the Galaxy. It is also known that many lines caused by excited atomic hydrogen and other elements exist in the millimeter range. These lines correspond to transitions between energy levels with large quantum numbers. This effect was predicted in the U.S.S.R. by Kardašev (1959) and discovered also in this country by Soročenko *et al.* (1964). Excited hydrogen lines are a very effective tool for investigating the distribution and movements of regions with strongly ionized interstellar gas. Although the line-brightness temperatures in the submillimeter range are smaller than in the centimeter range, the spectral density must be considerably greater than the thermal radiation density of the galactic continuum. For the brightest nebulae, the expected hydrogen line-flux densities in the 10–0·05 mm range (quantum number $n = 50$–10) are $(3 \times 10^{-18}\ \mathrm{wm}^{-2}) - (3 \times 10^{-12}\ \mathrm{wm}^{-2})$ (for $\Delta f/f = 10^{-4}$).

C. 'INFRARED STARS' AND QUASARS

In recent years, hitherto unknown sources of electromagnetic radiation have been discovered. These are the 'infrared stars', for which the maximum in the spectrum intensity falls in the wavelength range between 3 and 20 microns, corresponding to a black-body temperature of only 700 °K. It is very probable that such sources may be detected in the longer submillimeter range. Radio-astronomical and optical observations show that the maxima of intensity of the strongest sources, the most intense superstars and remnants of supernovas, must be in the submillimeter or infrared ranges. This radiation possesses a diversity of characteristics. In particular, radiation in this range has variable intensities, is strongly polarized, has an unusual spectrum, etc.

Investigations in the submillimeter and infrared ranges may be of decisive importance for revealing the nature of these objects, and also for resolving the related problems (formation and evolution of the galaxies, model universes studied with the help of the most distant sources, mechanisms for the acceleration of cosmic rays, finding of extraterrestrial civilizations). The expected flux densities from the brightest sources in the wavelength range close to 1 mm must be about 10^{-24}–10^{-25} wm^{-2} cps^{-1}, that at $\Delta f/f = 30\%$ gives 10^{-12}–10^{-13} wm^{-2}.

D. PLANETARY ATMOSPHERES

Spectral observations in the millimeter and submillimeter ranges are extremely important for revealing the chemical composition, pressure and temperature distributions in the atmospheres of the planets. The composition and conditions in planetary atmospheres are practically uninvestigated. It is known that in the millimeter and submillimeter ranges there are large resonance lines and bands of molecules such as those to be expected in planetary atmospheres: H_2O (13·5 mm, etc.), O_2 (5 mm and 2·53 mm), CO (2·61 mm, 1·3 mm), NO (1·99 mm and 1·2 mm), etc.

The investigation of the spectral features of planetary radiation will allow us to detect the existence of certain molecules in the atmosphere. Measurements of the shape and intensity of spectral lines will help to determine the height distribution of pressure and temperature. In the submillimeter range, flux densities may be equal to 10^{-20}–10^{-22} wm^{-2} cps^{-1} or 10^{-9}–10^{-11} wm^{-2} in the relative wave band $\Delta f/f \approx 30\%$.

E. SOLAR RADIATION

Submillimeter solar radiation is a source of information about the deepest layers of the chromosphere. In particular, the measurement of spectra, intensity, polarization, and time-dependence of radiation from the limb and active regions on the solar disk, connected with flocculae and spots, gives reliable data about the magnetic fields and electron densities above spots. These measurements help to clarify the nature of bursts connected with chromospheric flares, which play a significant role in geophysical phenomena.

A rather high instrumental resolving power (exceeding 30″) is a necessary requirement for these observations.

3. Instrumental Techniques

The state of submillimeter astronomy techniques is characterized by an intermediate position of this wavelength range. The review by Putley (1963) makes it unnecessary to restate all the methods of submillimeter radiation detecting.

At the present time, superheterodyne very wide band receivers with crystal-mixers at the input are used in the long-wave part of the submillimeter range (Cohn *et al.*, 1963). Optical methods are represented by Goley cells, bolometers of various kinds (including the superconducting type and also germanium cooled to liquid-He temperature). The most promising detectors for the submillimeter range seem to be photoconductive detectors and cooled bolometers with semi-conducting sensitive elements (In-Sb, Ge). Radiometers with such receivers have been developed and used for ground-based astronomical observation in England, U.S.S.R., U.S.A., and France (Low, 1961; Putley, 1965; Rollin, 1961; Popov, 1965; Karlova and Karlov, 1966; Arams *et al.*, 1966; Besson *et al.*, 1965). Figure 4 shows, for example, a submillimeter radiometer with an In-Sb sensitive element developed in the Moscow Institute of Radiotechnics and Electronics by Vystavkin and Popov. A significant success must be pointed out in the field of submillimeter guidance, filtering, and techniques of

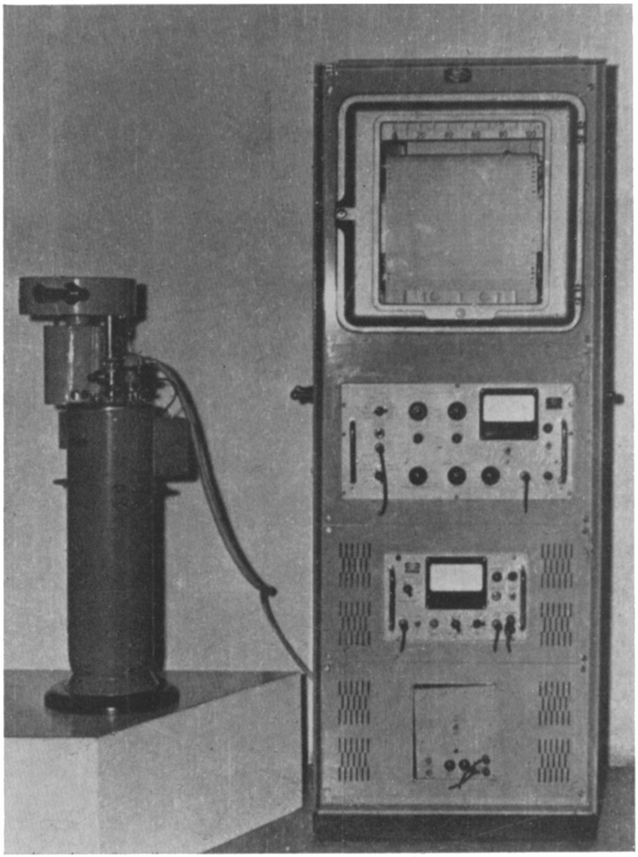

FIG. 4. *A submillimeter radiometer with sensitive element of In-Sb developed in the Institute of Radiotechnics and Electronics (Moscow) by A.N. Vystavkin and E.J. Popov.*

measurements, in particular, in those of polarization and interference (Colleman, 1963; Vinogradov *et al.*, 1967). In Figure 5 is represented a submillimeter Fabry-Pérot interferometer using wire-grid elements, developed in the Moscow Lebedev Physical Institute (in the laboratory led by A. Prohorov) by Natalia A. Irisova and her collaborators E. Dianov and E. Vinogradov.

In submillimeter radiometers, multimode detectors are used instead of the single-mode ones, which were developed for the microwave range. In the submillimeter detectors the linear dimensions are larger than the middle wavelength; furthermore, each element of the detector transforms the radiation incident on it independently of the others. This characteristic causes some modifications in the expressions for antenna directivity and noise-threshold sensitivity of radiometers. These problems have been investigated by a number of workers (Williams and Chang, 1963; Karlov and Prohorov, 1964; Popov, 1965; *et al.*).

For some calculations of sensitivity Planck's representation must be used instead of that of Rayleigh-Jeans, in those cases when the energy of one quantum is of the same order or more than kT. In the opposite case, when we consider a high-temperature submillimeter radiation, it is possible to keep a Rayleigh-Jeans representation. These problems have been investigated in detail by Karlov and Čihačev (1959) from the Lebedev Institute, and by other authors.

The main difficulties in the development of submillimeter-astronomy techniques

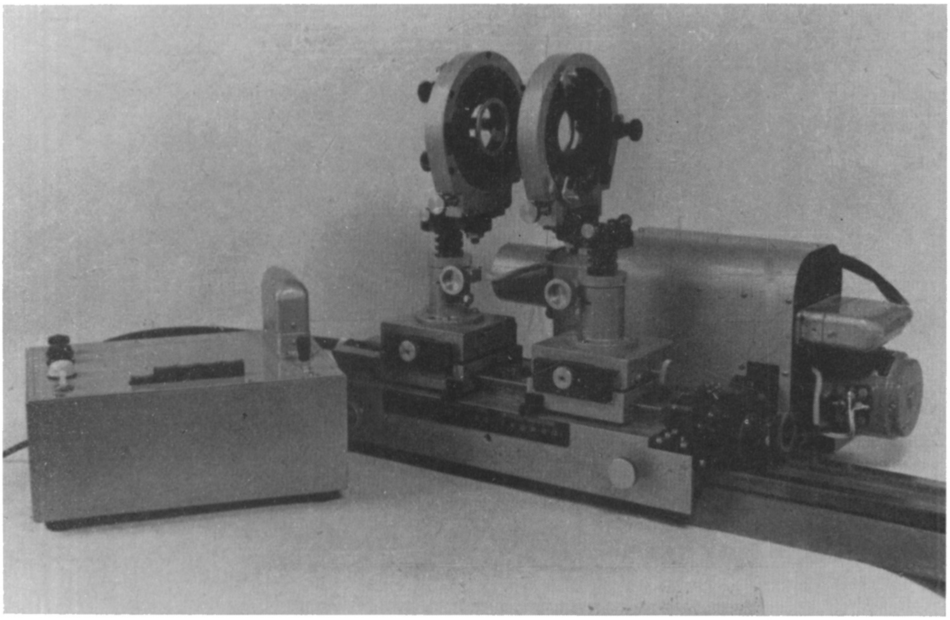

FIG. 5. *Submillimeter Fabry-Pérot interferometer with wire-grid elements developed in Moscow, P.N. Lebedev Physical Institute, by N.A. Irisova, E. Dianov and E. Vinogradov.*

arise from the necessity of taking the receiving equipment out of the Earth's atmosphere, or at least of partially excluding its influence. Naturally, the simplest method consists of elevating the radiometers on mountains, where the humidity is less than 1 gm^{-3} during most of the year. Such attempts were undertaken by several groups, among which is the group (Bastin *et al.*, 1964; Baldock *et al.*, 1965) from the Queen Mary College (England) which conducted observations at an altitude of about 2000 m at wavelengths 1–4 mm. The group from Gorky Radiophysical Institute (U.S.S.R.) has stations on Elbrus and Aragac (Caucasus), and also on East Pamyr (Drjagin *et al.*, 1966; Gorohov *et al.*, 1962; Kisljakov and Plečkov, 1964). During these observations, atmospheric attenuation and submillimeter radiation from the Sun and the Moon have been chiefly investigated. All of these experiments gave very interesting data for the Sun and especially for the Moon in the long-wave part of the submillimeter range. At the same time, the importance of carrying out the observations at the highest altitudes is evident, especially for the wavelengths shorter than 1 mm.

The results of measurements by Fedoseev (1966) indicated the observed attenuation caused by a non-resonant absorption in oxygen may considerably exceed that of water vapour even in the winter. For this reason the calculated attenuations for 1–1·5 mm wavelengths were somewhat underestimated.

From the above it is evident that for submillimeter astronomy the most promising methods are those of space astronomy.

One of the relatively simple techniques of space astronomy consists of elevating the equipment by stratoplanes and balloons. The first published results obtained by such a technique for far-infrared observations (Bater *et al.*, 1967; Woolf *et al.*, 1967) are very interesting. Figure 6 gives the results of the first attempts to measure the water-

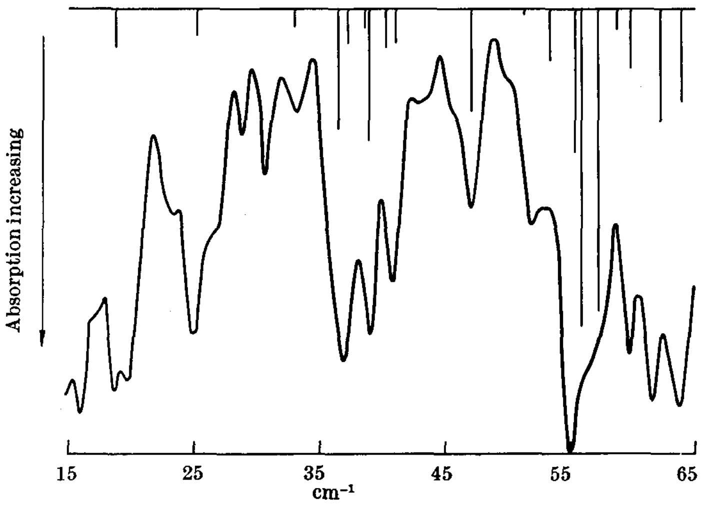

FIG. 6. *An observed spectrum of the sky at 40000 ft. in the range 15–65 cm^{-1} (from Bater et al., 1967)*

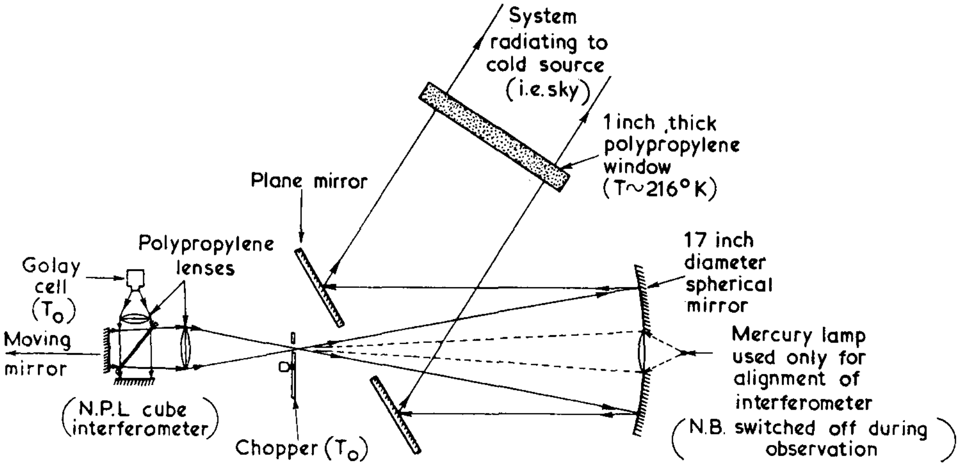

FIG. 7. *Schematic diagram of the experimental arrangement of the telescope and the modular interferometer (Bater et al., 1967).*

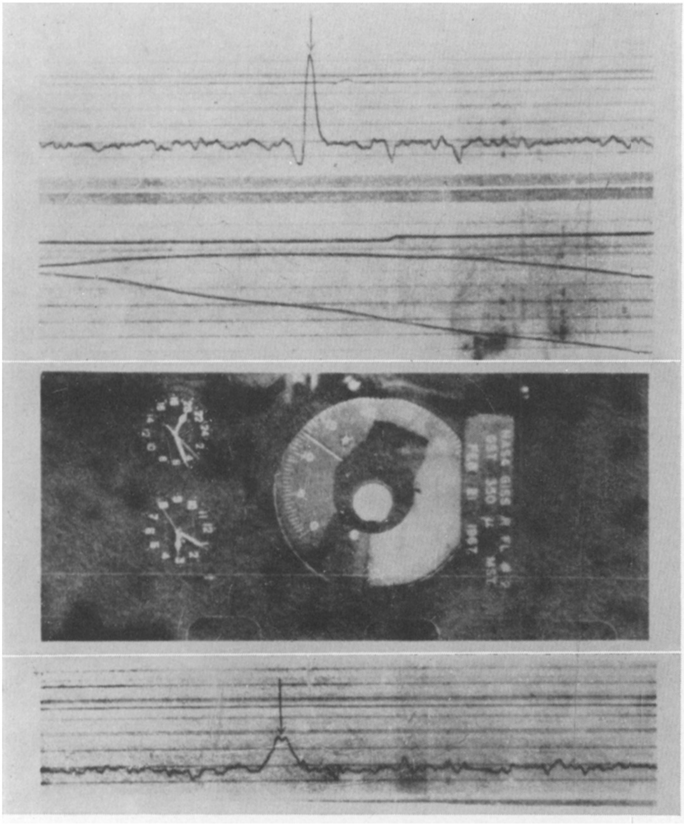

FIG. 8. *Moon radiation in the submillimeter wave range ($\lambda = 320$ microns) obtained by Woolf et al. (1967).*

vapour spectrum, which were obtained by Gebbie's group on the stratoplane 'Gallileo' at an altitude of 40000 ft. in the region of 15–65 cm^{-1}. The measurements were made with the help of a submillimeter Fourier spectrometer (Figure 7). The balloon technique has been widely used in recent years for infrared astronomy. The first attempt at balloon submillimeter investigations has been made recently by Woolf and Low and their colleagues from the Hoddard Institute for Cosmic Researches (U.S.A.).

In the gondola of a balloon, which was flown up to 98000 ft., was placed a modulated radiometer with a receiver involving a Ge He-cooled bolometer. A sensitivity of 7×10^{-14}w $cps^{-1/2}$ was obtaine dat temperature 1·8 °K. An interesting feature of the experiment was the use of the exterior vacuum for pumping the dewar. The measurements were made in the wavelength range of 300–450 microns with the maximum at 320 microns. Modulation was performed by oscillation of the reflecting mirror so that the radiometer recorded intensity gradients of the sky radiation. Although the only source observed was the Moon (Figure 8), an upper radiation-flux limit was estimated which turned out to be equal to $2 \cdot 10^{-23}$ w cm^{-2} cps^{-1}. This first attempt to track the sky in the submillimeter region displays the great possibilities of balloon submillimeter astronomy.

Of much interest also are the explorations in the field of balloon submillimeter

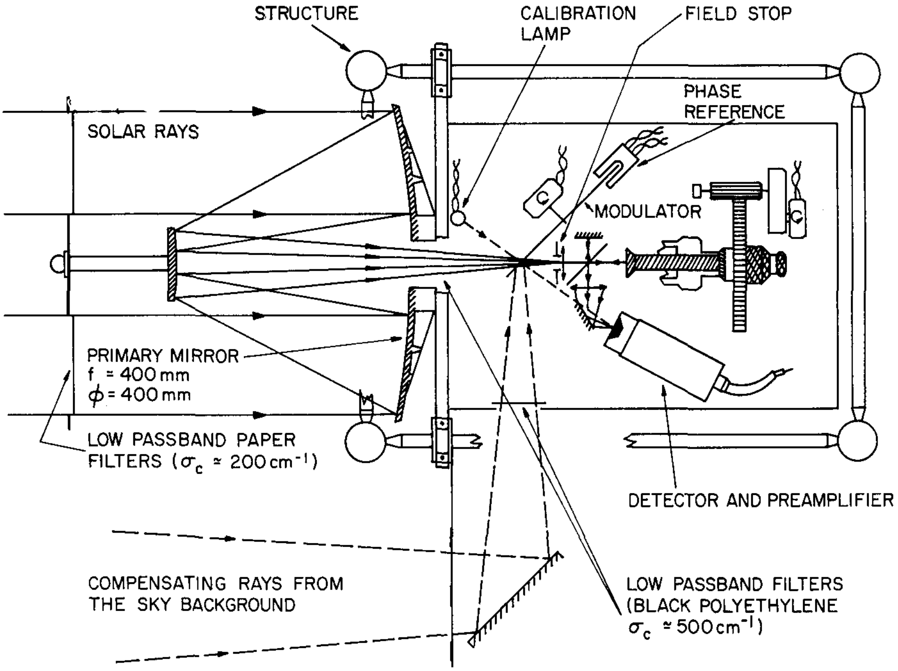

FIG. 9–11. *Submillimeter radiometer and some parts of the installation flown in the gondola of the balloon of the Meudon Observatory (Gay et al., 1967).*

astronomy by J. Gay and others, which started about 2 years ago in the Meudon Observatory (France) under the guidance of Lequeux (Gay *et al.*, 1967). Using hydrogen balloons of the French National Centre for Cosmic Researches, together with a stabilized gondola having a pointing precision 10–20 sec of arc, this group made spectral investigations of the Sun with a resolution of 0·3 cm^{-1} in the range of 50 to 2300 μm. The experiment was planned to obtain a spectrum of residual water vapour of O^{18} H_2 and OHD and, possibly, the solar C^+ line at 156 microns. It was intended to make the absolute calibration on the ground, and relative measurements on-board, which were expected to give spectrophotometry of the Sun with an accuracy better than 5%, which would be essential for selecting models of the photosphere.

As a first step this group has used a 40-cm Cassegrain telescope and a Fourier interferometer with a mylar beam-splitter. The detector is of Golay type, built in France by ONERA with a modulation frequency of 10 spc (Figure 9). After synchronous detection the output voltage is converted into variable frequency pulses, sampled in synchronism with the motion of the mirror of the interferometer, and recorded by an on-board tape recorder. The balloon radiometer apparatus of the Meudon Observatory is shown in Figure 10 and 11. The first flight was made on June 24, 1967, with the equipment operating in the wave band 50–300 μm. The measured solar spectrum

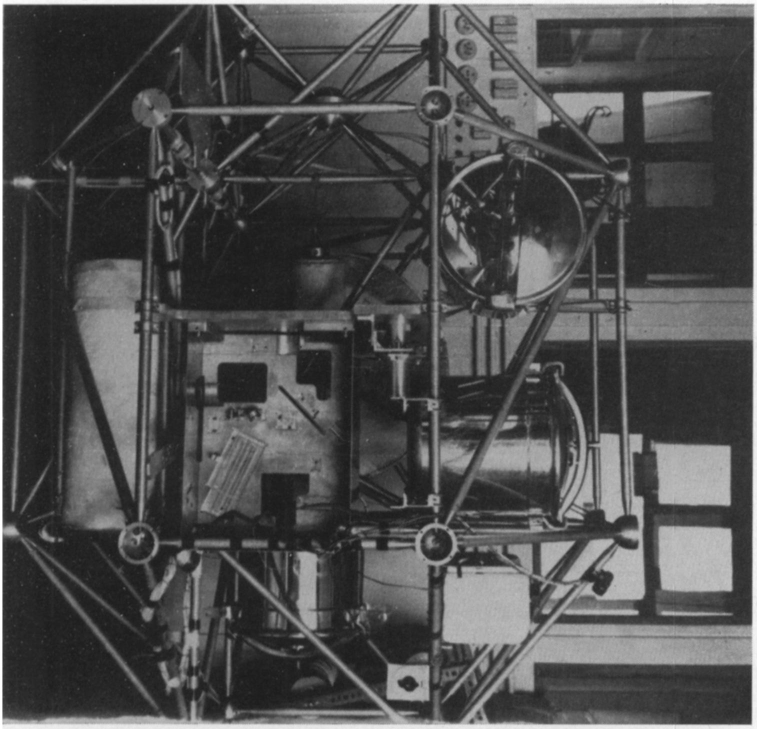

FIG. 10.

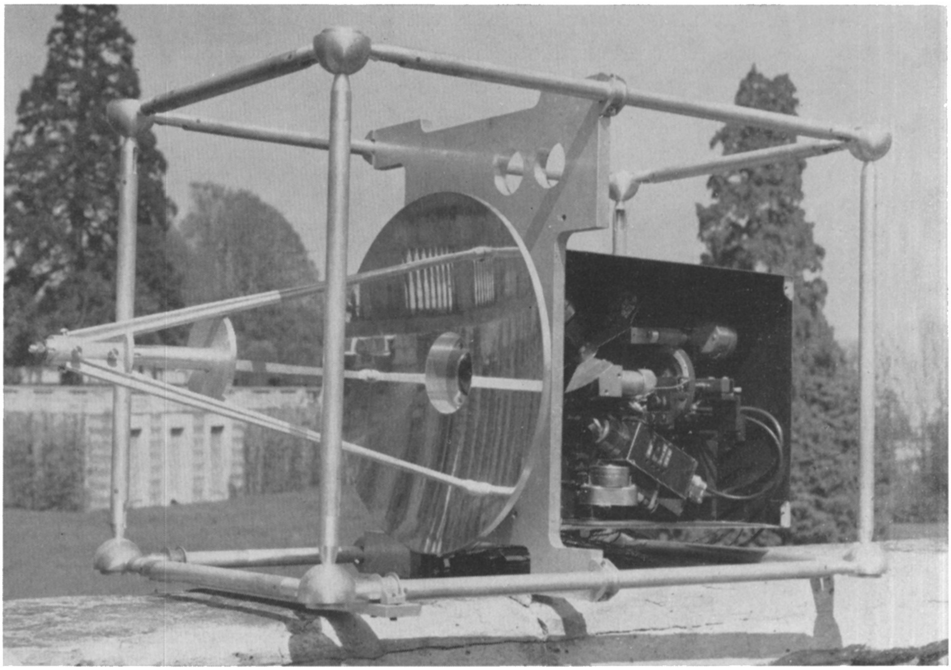

FIG. 11.

(after corrections) is shown in Figure 12. For measurements needing higher sensitivity, a helium-cooled bolometer of the Putley type is under study. The measurement of the sky background near 1 mm is under investigation, with a wide field apparatus allowing continuous comparison of the sky temperature with the temperature of the helium bath. Balloon observations of planets and quasars are supposed to be made with a reflector of 1 m to 1·40 m diameter and with a very sensitive detector. Ground observations are also planned at an altitude of 3140 m, above 900 microns and in the 350 micron 'window'. The above-mentioned difficulties increase considerably when satellite technique and rockets are used for submillimeter observation.

Two problems remain to be solved, and will determine the future success of submillimeter space astronomy. These are:

(a) The development of a high-precision mirror antenna suitable for the submillimeter wavelength and supplied with tracking systems;

(b) The use of cooled submillimeter detectors on satellites.

For the first problem, the difficulties may be somewhat smaller than for Earth radio astronomy. The absence of wind and weight loads will make engineering calculations easier. The main difficulties, probably, will be the assembling of highly directive submillimeter antennae as well as tracking after predicted points of the sky. These problems are very similar to those arising in optical space astronomy.

The detector-cooling problem, under rocket and satellite conditions, is a rather complicated one. The requirement for cooling to the temperature of liquid helium (since no semi-conductor or other sensitive elements have been developed operating at a higher temperature) requires a volume filled by liquid helium. The storage of such liquid requires some economical micro-cooler or cryostat capable of storing liquid helium during some long period in the absence of gravity, and in a high-vacuum and low-temperature environment, which is also to withstand vibration and overloading during the active part of trajectory. The situation is analogous to that arising in superconductivity space experiments (for cosmic rays or space relativity investigations). In this connection the results of methodical experiments which have been obtained recently by Lidie V. Kurnosova's group at the Levedev Physical Institute (Anaškin *et al.*, 1967) are of interest. In this experiment the possibility of using superconductive devices on cosmic vehicles was tested. Helium at overcritical pressure (2·4 atm and an initial temperature ≈5·2 °K) was used as the cryogenic agent. Two superconducting

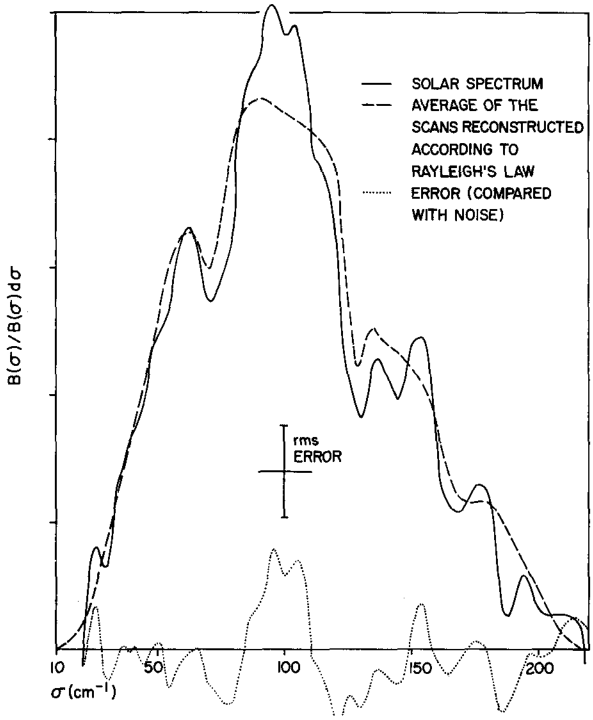

FIG. 12. *Solar spectrum in submillimeter band obtained by the Meudon group (Gay et al., 1967).*

solenoids with magnetometers and six thermometers were installed inside the helium container (volume ≈11·5 l). The experiment was carried out on the sputnik Kosmos-140 and resulted in the statement that such a one-phase method of storage at low temperature (up to ~7 °K) can be used in the conditions of weightlessness.

If these difficult technical problems can be solved, we may hope that a new and promising branch of astronomy, namely submillimeter astronomy, will arise and give us surprising results.

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DISCUSSION

F.J. Low: The last experiment that you discussed. When was it flown, and was it a complete success?.

A.E. Salomonovič: It was flown this spring, and the results were presented at the Tenth International Conference on Cosmic Rays in Canada.