Summer Student Lecture Notes
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COSMIC BACKGROUND RADIATION*

Prediction

In 1934, Tolman studied the behavior of radiation in an expanding universe. At the time, the calculation was a theoretical one; there was no real reason to suspect that a radiation field filled the universe. The result of this calculation was that, given an initial blackbody spectrum of temperature T_o at epoch t_o, then there will exist a blackbody spectrum of temperature T_1 at time t_1, such that

$$T_1 = T_o\, R(t_o)/R(t_1),$$

where R(t) is the scale factor of the expansion. We can understand this result in a heuristic way by the following argument, similar to one used in studying the thermodynamics of ideal gases. Imagine a cavity with perfectly reflecting walls. Let the size be much less than the size of the visible universe (i.e. $\ll cH^{-1}$). Then, if we allow the box to expand, without creating or destroying any photons, we find that the photon gas must cool. This can be thought of as the result of doing work in expanding the box. Another way to think of it is that, in a perfectly reflecting cavity, the radiation field can be expressed as made up of a superposition of normal modes, where each mode has an integral number of wavelengths in the box. But as the box expands, $\lambda_n(t) \propto R(t) \propto \frac{1}{\nu_n(t)}$ for each mode n. Since Planck's formula for a photon gas says that the number of photons per mode is given by $\mathcal{N}_n = (e^{h\nu_n/kT} - 1)^{-1}$

then the temperature must decrease linearly with the frequency, and

*Much of these notes has been unabashedly lifted from two excellent, and highly complementary sources, Gravitation and Cosmology, S. Weinberg, and Physical Cosmology, P.J.E. Peebles.

hence, as the scale factor of the expansion.

Based on this theoretical background, Gamow and Alpher, in 1948, studied tb problem of the production of the elements. There are a number of reasons why their analysis was wrong. However, the thought processes are interesting, and worth reviewing. Besides, they got the right answer. Some earlier treatments of the problem had been made, assuming that element formation took place in a static, equilibrium situation at some hot stage of the universe. With the current view of a continually expanding universe, Gamow and Alpher decided to attack the problem again. They suggested that, at high temperatures, only free neutrons, protons, and electrons could exist. The key factor in building up the heavy elements is the formation of deuterium, according to the reaction

$$n + p \rightarrow d + \gamma$$

However, at high temperatures, the reverse reaction (photodissociation) breaks up all the deuterium. At about 10^9 K, deuterium can begin to accumulate. Gamow argued that at around this temperature, there must be an appreciable chance of n's and p's colliding, so that the reaction could take place. Not too great, however, because we still want the universe to consist mainly of atomic hydrogen. The calculation they went through was somewhat like setting

$$\sigma n v t \sim 1$$

where σ is the neutron proton cross section, v, the mean thermal velocity, t, the time available at that temperature, and n, the density, all to be determined at the time when $T \approx 10^9$ K. Since radiation energy density varies as $R(t)^{-4}$, it dominates the matter energy density, which goes as $R(t)^{-3}$ at early times. Thus, the dynamics of the expansion can be found from the temperature of the radiation alone, and knowing σ and v, n was calculated to be $\approx 10^{18}$ nucleons cm^{-3}. By the time n gets down to $\approx 10^{-6}$ cm^{-3}, roughly the current density, $T \approx 10$ K. Alpher and Herman refined the calculation, and got $T \approx 5$ K. Problems with this argument include the objection that element building stops at the mass 5 gap above helium in simple expanding universe models, and that the neutron-proton ratio was probably only about 0.2 at the proper time. With the explanation of element formation as part of stellar evolution, this line of argument was dropped, and the idea of a primeval fireball neglected until the early 1960's.

In 1964, Dicke was concerned with the singularity at which all the mass energy of the universe originated, and at which the expansion began. He preferred to relegate the origin of mass energy to an earlier phase of the universe, which then goes through successive oscillations. However, in order to destroy the heavy elements from the previous oscillation, he needed a hot phase of the universe, around 10^{10}K. The fireball was reborn.

Discovery

At the Holmdel, N.J. laboratories of Bell Tel, Penzias and Wilson constructed a large horn antenna (Fig. 1) designed to receive signals from the Echo satellite, at a wavelength of 7.5 cm. They were trying to track down all possible contributions to the system noise, and were unable to account for about 3.5 K. The group at Princeton had already begun the search for the remnant of the fireball, and realized the significance of the Penzias and Wilson result. They visited the Holmdel labs, and in 1965, published companion papers, the first entitled "A Measurement of the Excess Antenna Temperature at 4080 MHz", and the second an explanatory one by Dicke, Peebles, Roll and Wilkinson. But was this excess radiation truly the remnant of a primeval fireball? A few critical experiments had to be done.

Spectrum

The first crucial test was to determine that the radiation followed the predicted Planck spectrum

$$I(\nu) = \frac{2h\nu^3}{c^2}\left(e^{h\nu/kT} - 1\right)^{-1}$$

For $\frac{h\nu}{kT} << 1$, this reduces to the form

$$I(\nu) \approx \frac{2kT\nu^2}{c^2}$$

This is the same as the definition of antenna temperature for radio astronomy, so that in the long wavelength (Rayleigh-Jeans) part of the spectrum, the confirmation of the blackbody nature of the background reduced to measuring a constant antenna temperature as a function of wavelength, i.e., ≈ 3 K. In Fig. 2 is plotted the intensity vs. frequency for blackbody radiation of different temperatures. In the region spanned by a 3 K blackbody, the antenna temperature from other sources of radiation is plotted in Fig. 3.

The first Princeton experiment was designed to work at a wavelength of 3.2 cm, and thus soon provided an independent confirmation of the Penzias and Wilson result. Today, the blackbody nature of the spectrum has been well established at wavelengths longer than that of peak intensity

$$\lambda_{max} = 0.51\ T_0^{-1}, \text{ which} \approx 0.19 \text{ cm at } 2.7 \text{ K.}$$

Table 1 gives a list of a number of determinations of the thermodynamic (as opposed to antenna) temperatures of the background radiation. Most of the long wavelength results came from ground-based radiometers. Below about 3 cm wavelength, the antenna temperature drops exponentially (Wien region), and the emission from the earth's atmosphere becomes a major source of difficulty. The experiments are then often done at mountain altitudes, and in "windows" of the atmosphere at ≈0.9 and ≈ 0.3 cm. Shortward of that, however, either balloons or rockets must be used.

In 1941, McKellar discovered that absorption lines in the cyanogen radical in the direction of Zeta Ophiuci came from both the ground state and the first excited rotational state. He could not rule out the possibility that collisional or pumping mechanisms, for example, were responsible for the excitation. So he quoted a value of $T \approx 2.3$ K for the equivalent blackbody temperature which would produce the excitation observed, in the absence of other processes. This result applied at a wavelangth of 2.6 mm. It was not until after the masurements of the background at 7.5 and 3.2 cm that the significance of this measurement was realized. Further theoretical work dismissed all other possible rotational excitation mechanisms. In addition, data from a number of stars have all given results between 2.7 and 3.7 K. It is unlikely that local excitation mechanisms would be so uniform. CH and CH^+ have also been used to set limits on the background temperature at wavelengths of 1.32, 0.56, and 0.36 mm.

There are some problems with the infrared rocket temperature determinations being too high, but there are many observational difficulties, as well as the possibility of line emission in this region. Pursuit of this subject is left to the reader.

Observing the 3 K Background

A picture of some of the early apparatus used at Princeton is shown in Fig. 4. In most other radio astronomical observations, we observe both the unknown source, and a reference in the sky, and subtract them to remove systematic effects. This is true in spectroscopy, where the off-of-line regions of the spectrum, and off-source spectra are used to determine the instrumental baseline.

This is also true of single dish measurements of continuum sources, where observations are taken on and off the source to determine its flux. Interferometry, by its very nature, is sensitive to differences in brightness over certain spatial scales. However, with such a broad spectrum, if the blackbody were indeed universal, then there is no astromical "off". It was thus the task of the observers to account extremely carefully for all systematic effects in their instruments.

The basic procedure used was switching rapidly between a known and reference source, a technique developed by Dicke in 1945, and in common use today. The reference source in this case was a dewar of liquid helium, at 4.2 K. What was then measured was the difference between the sky temperature and 4.2 K. A block diagram of an early system is shown in Fig. 5.

It is an interesting point to realize that the size of the antenna does not affect the sensitivity of these measurements. This is always true, as long as the source of radiation is much larger than the beam size. Increasing the aperture size merely increases the forward gain, or directivity of the antenna, not the total power received. In fact, small aperture antennas were used to degrade the respnse to localized sources of radio flux, as well as to make the apparatus more manageable. A great deal of effort went into the design of the antennae, waveguides, switches, and cold loads in these experiments, and details can be found in the references. At around 1 cm, the biggest contributions to the atmospheric temperature are from water vapor and oxygen. The atmospheric contribution is subtracted out by tipping the antenna away from the zenith, and subtracting out the observed dependence on the secant of the zenith angle. The residual is the desired background temperature (hopefully).

Large Scale Isotropy

Another important test of the cosmic nature of the background radiation is its isotropy. Even as the galaxies recede from us in any direction we look, so should we see the redshifted fireball to be the same in all directions. The results of observations were that the radiation was amazingly isotropic.

Ideally, these observations are much easier to do than the absolute measurements because they measure only the difference between the radiation from different parts of the sky. Fig. 6 shows one of the instruments used to measure this isotropy. However, at some level, we expect to see an anisotropy from our peculiar motion through the universe, that is, our departure from the general Hubble expansion. By using the Lorentz transformation, it can be shown that an observer moving with a speed v with respect to the frame of blackbody radiation sees a blackbody spectrum described by

$$T(\Theta) = T_o(1- v^2/c^2)^{\frac{1}{2}} (1-v/c \cos\Theta)^{-1},$$
$$\approx T_o(1 + v/c \cos\Theta) , \quad v/c \ll 1,$$

where Θ is the angle between the velocity vector and the direction of observation. Table 2 shows some of the possible contributions to our peculiar velocity, where the positive x-axis is defined by $\alpha = \delta = 0$, and the +y axis by $\alpha = 6^h, \delta = 0$. ϵ represents the fractional deviation from the Hubble flow because of the influence of the Virgo cluster. At any rate, the expected amplitude of the variation across the sky is of order

$$v/c \approx 200 \text{ km sec}^{-1}/3\text{x}10^5 \text{ km sec}^{-1} \approx 10^{-3},$$

or a few millidegrees Kelvin. This very amall temperature is what makes the measurements so difficult. Earth-based observations often take place for over a year, in order to separate solar and sidereal effects. Balloon experiments, on the other hand, fly only at night, and therefore cannot see the full 24 hr cosine behavior, in a single flight.

To date, peculiar velocities through the radiation field have indeed been observed, but the results, on the order of a few hundred km sec^{-1}, are highly uncertain. The major uncertainty in these measurements is the subtraction of the Galaxy's contribution to the observed anisotropy. Recently, as the culmination of years of work by Rubin, Roberts, and their collaborators, a peculiar velocity has been detected from observations of the redshifts of galaxies. Discrepancies between these measurements, and the lateest background radiation velocities remain to be resolved.

Small Scale Isotropy

Measurements of isotropy on small angular scales help to rule out a more local origin for the radiation, from a large number of small sources. Or, it can place limits on the irregularities on the distribution of matter at the time of last scattering, when hydrogen recombination took place at a redshift of ≈ 1500. The early results of Conklin and Bracewell, that

$$\frac{\delta F}{F} \lesssim 2 \times 10^{-3}$$

where F is the purported flux from discrese sources in an angular scale of 10 arc minutes. If the sources are close by (within $r \approx cH^{-1}$) then the required source density to give a smooth distribution is

$$n_s \gtrsim 3000 \ h^3 \ Mpc^{-3},$$

where H_o = 100h km $sec^{-1} Mpc^{-1}$, and the mean distance between sources is

$$n_s^{-1/3} \lesssim 70 \ h^{-1} \ kpc,$$

which is about 5 orders of magnitude greater than the number density of large galaxies, and the mean separation an order of magnitude less than our distance to Andromeda. In addition, the sources must be randomly distributed, whereas, in the distribution of galaxies, we see clustering and anistropies on scales less than 10 Mpc, as well as some evidence for superclustering on larger scales. However, we see only optical objects out to a redshift of about 4, and the constraints would be relaxed somewhat if the sources of the radiation were all at redshifts $z > 10$. However, the limits on the small scale isotropy are constantly being lowered, and covering a broader range of angular scales. For a recent discussion by a proponent of discrete sources, see the article by Rowan- Robinson given in the references.

Implications of the Primeval Fireball

I merely list here some of the proposed effects due to the background radiation. See the references for discussions of any of these.

1) Most important, perhaps, the thermal history of the universe, including the determination of the entropy per nucleon, is crucial to the formation of primeval helium and deuterium. This field has received great attention, and is still a subject of much debate.

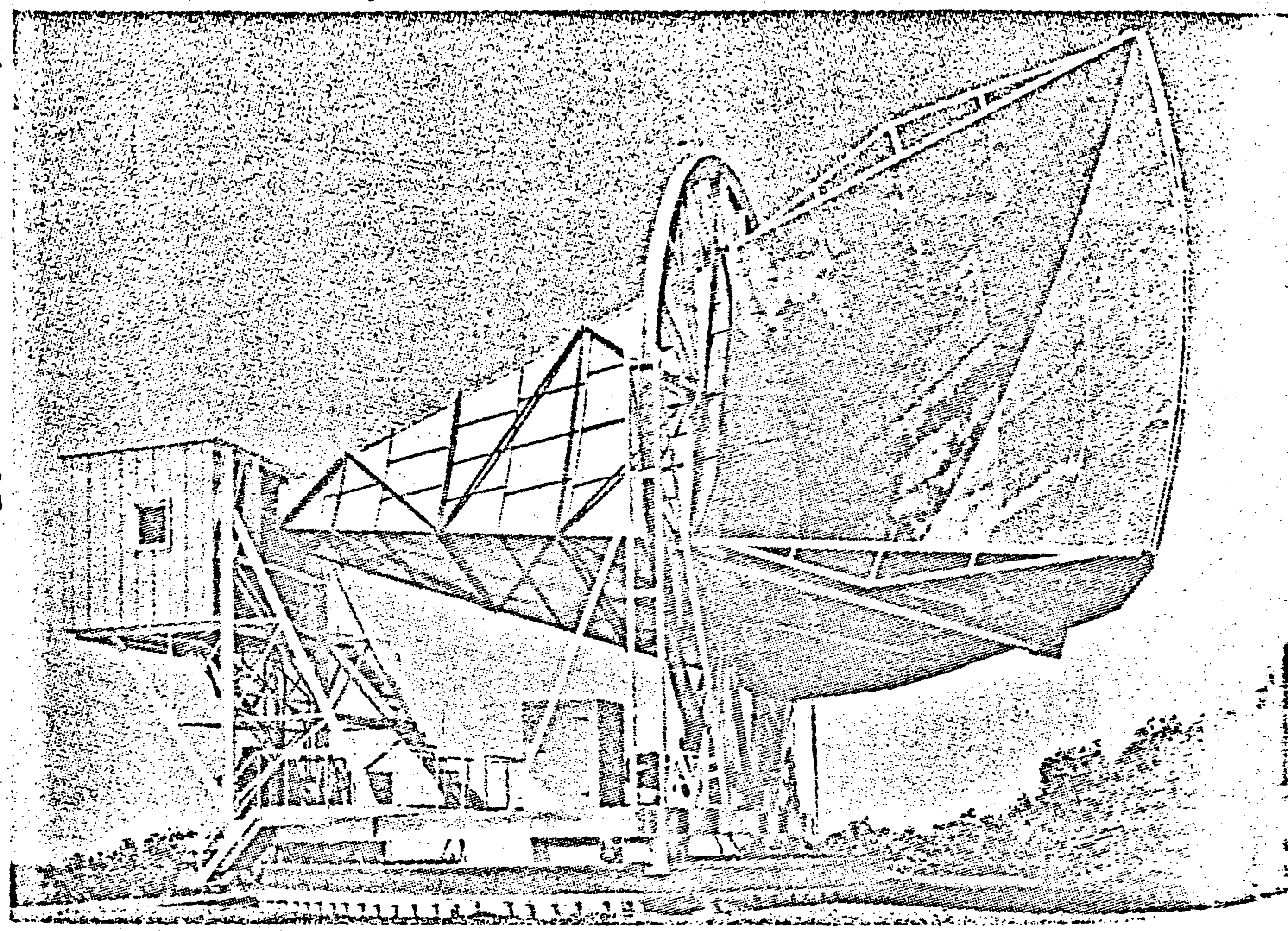
2) Formation of the soft X-ray background by inverse-Compton scattering by relativistic electrons has been suggested.

3) Interaction with high-energy cosmic rays has been considered for its implications of the N(E) distribution , and the origin of cosmic rays in general.

4) Detailed measurements of the spectrum may help probe the departures from the simple isotropic and equilibrium picture studied so far. Fluctuations in the spectrum and in the background may contribute to our understanding of the growth of irregularities in the universe, and the formation of galaxies.

a)

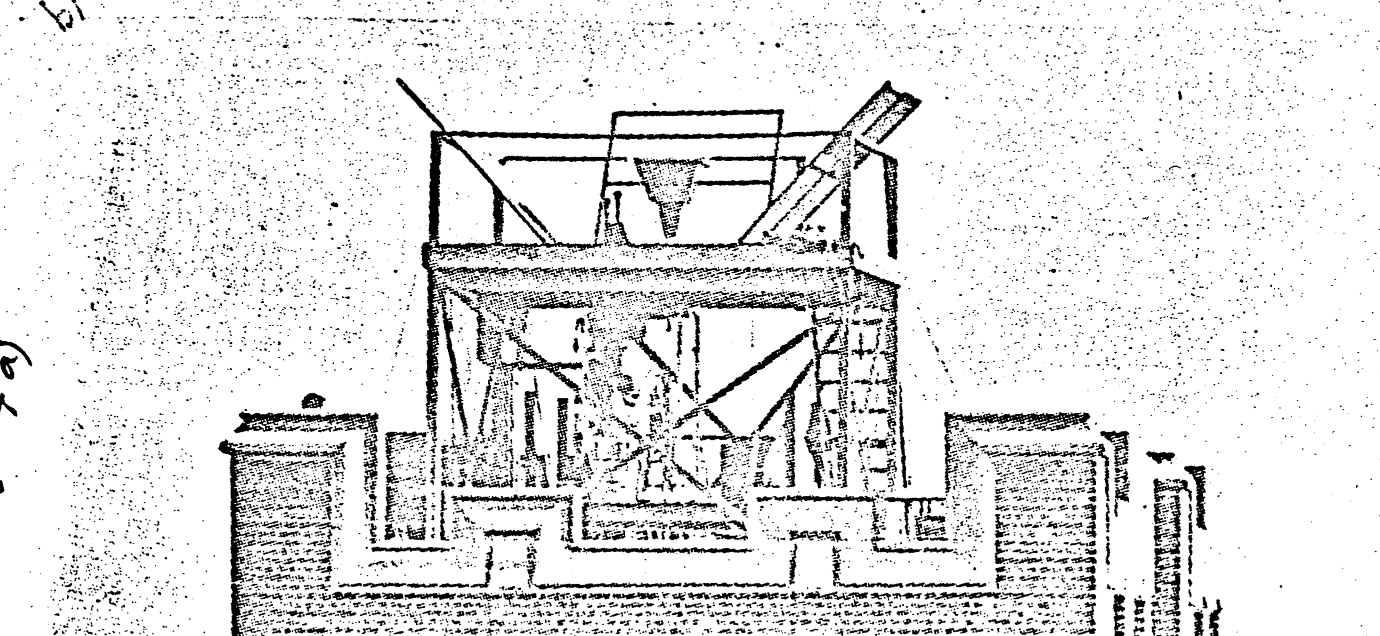
FIG. 1



HORN ANTENNA of the Bell Telephone Laboratories receiver at Holmdel, N.J., was originally designed to collect signals reflected from Echo satellites. This was the antenna with which Arno A. Penzias and Robert W. Wilson first detected the fireball radiation

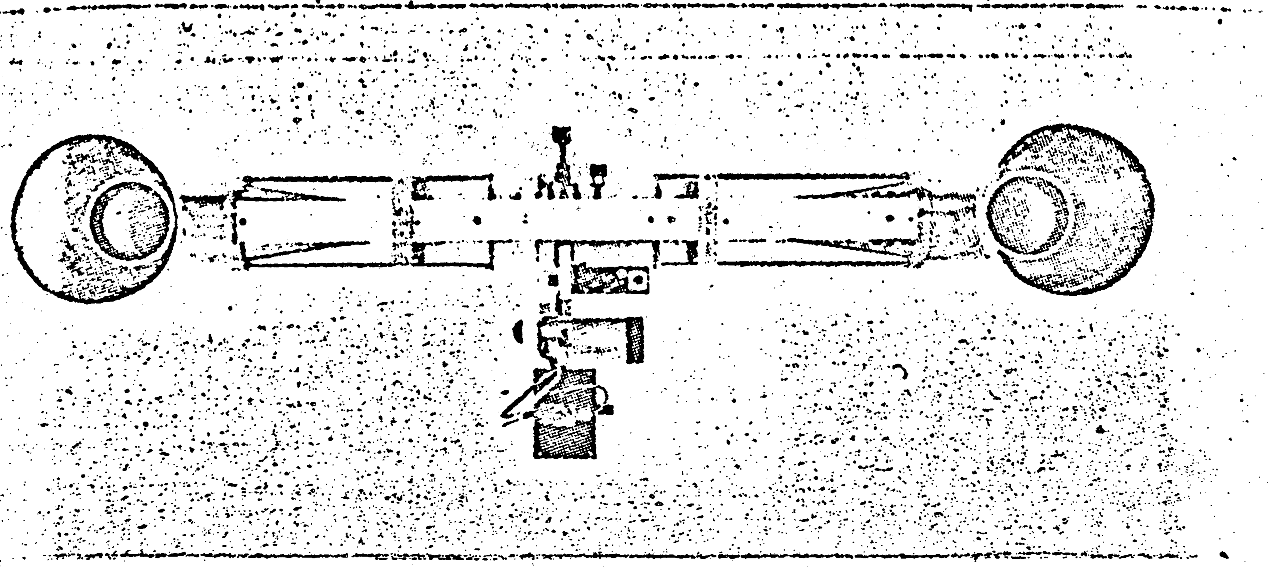
b)

FIG 4(a)



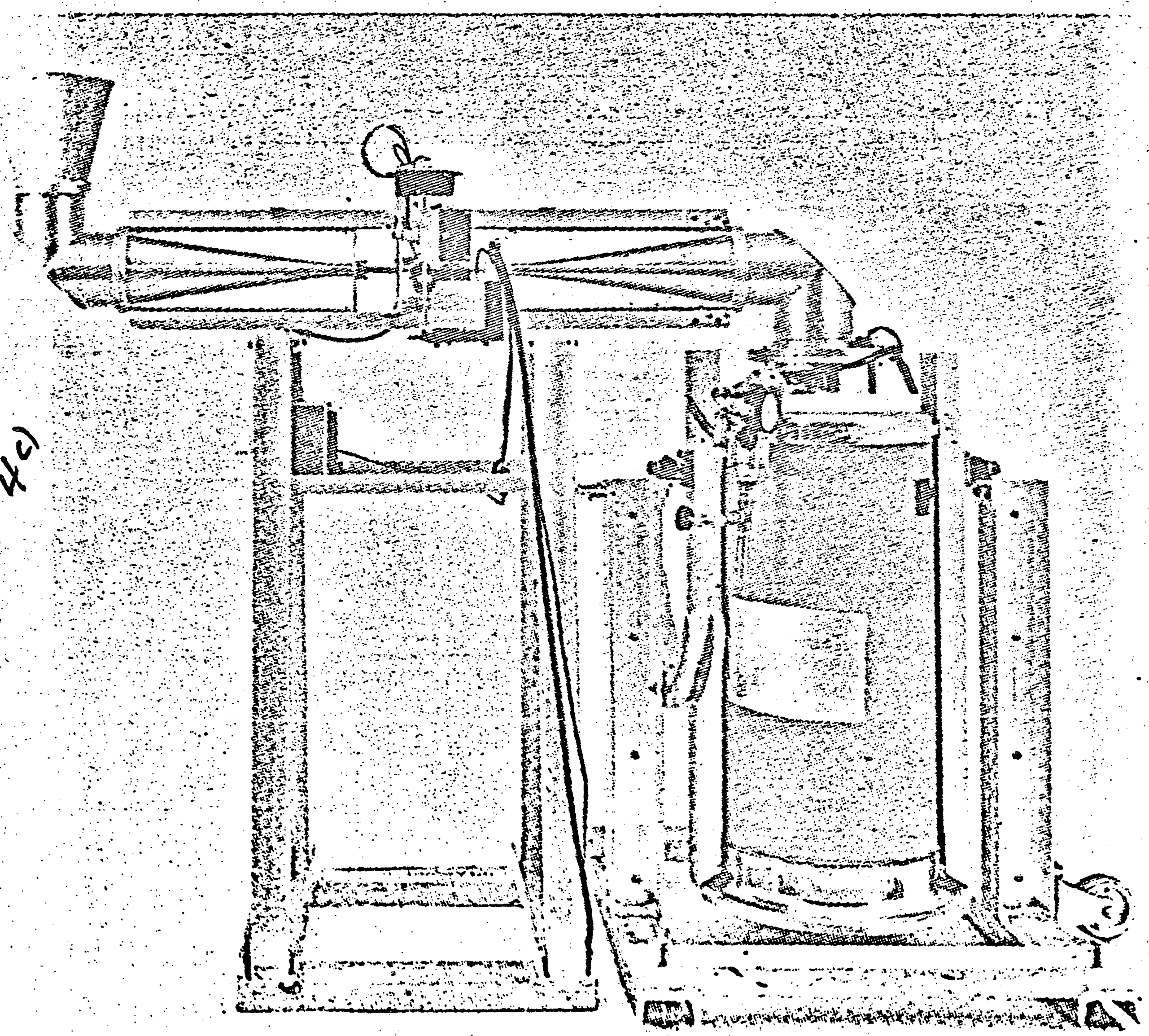
PRINCETON GROUP'S first fireball observations were made with an earlier version of the radiometer, here shown in position on the roof of the geology building. The slanted panels around the base are wire-mesh screens that help to keep out ground radiation

4 b)



[illegible]STRUMENT with which the primeval fireball is observed at [illegible] University is a recent version of the Dicke radiometer, [illegible] here from above. The antenna horns extend to the left and right and are directed upward to collect sky radiation; a switch, microwave receiver and amplifier are at the center. The instrument is operated both in this configuration and as illustrated below.

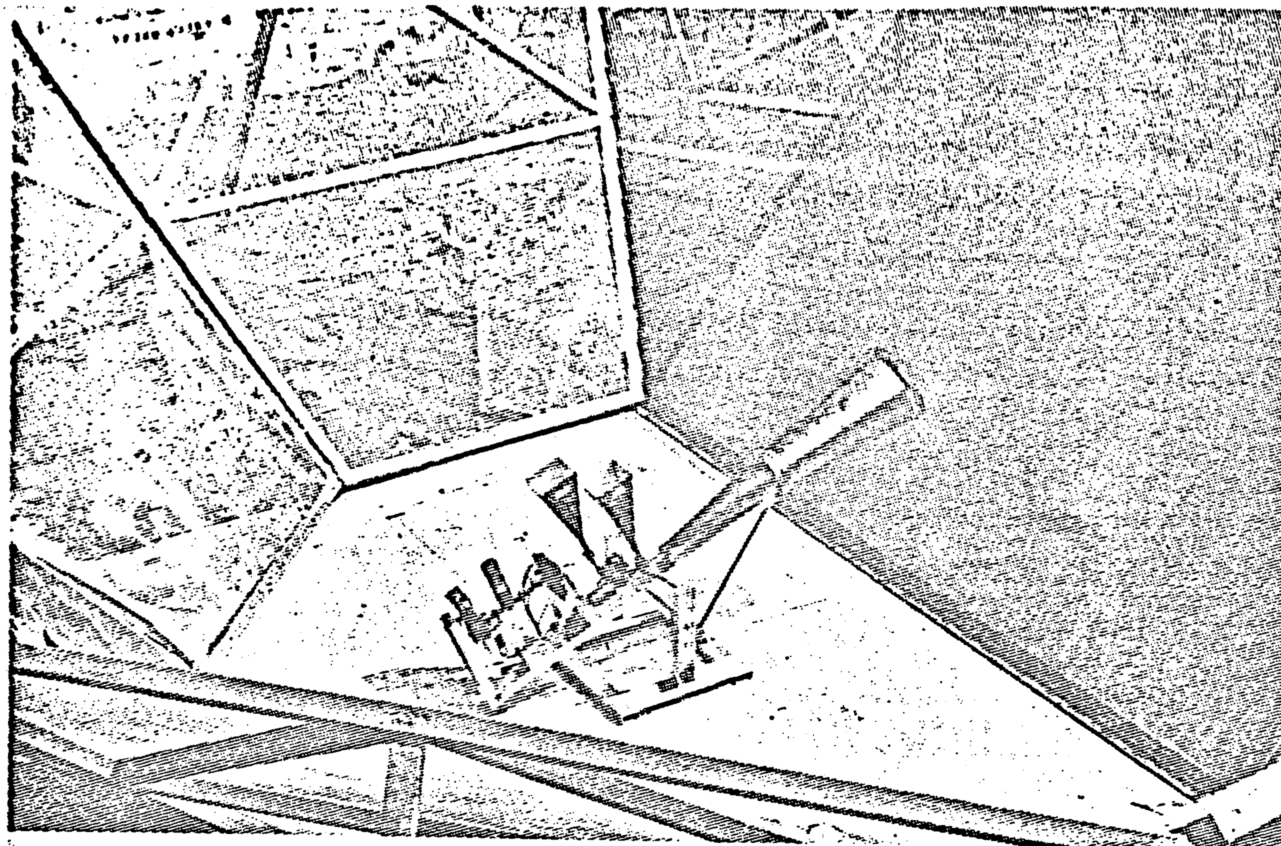
4c)



[illegible]ETER is seen in a side view with one of the horns in [illegible] receive radiation from the sky. The other horn of the [illegible] is coupled to a wave guide leading to a reference [illegible] side the orange Dewar flask. The source is immersed in boiling liquid helium and is therefore known to be radiating at 4.2 degrees Kelvin (degrees centigrade above absolute zero). The receiver input is switched back and forth between sky antenna and reference source and the intensities of the two are compared.

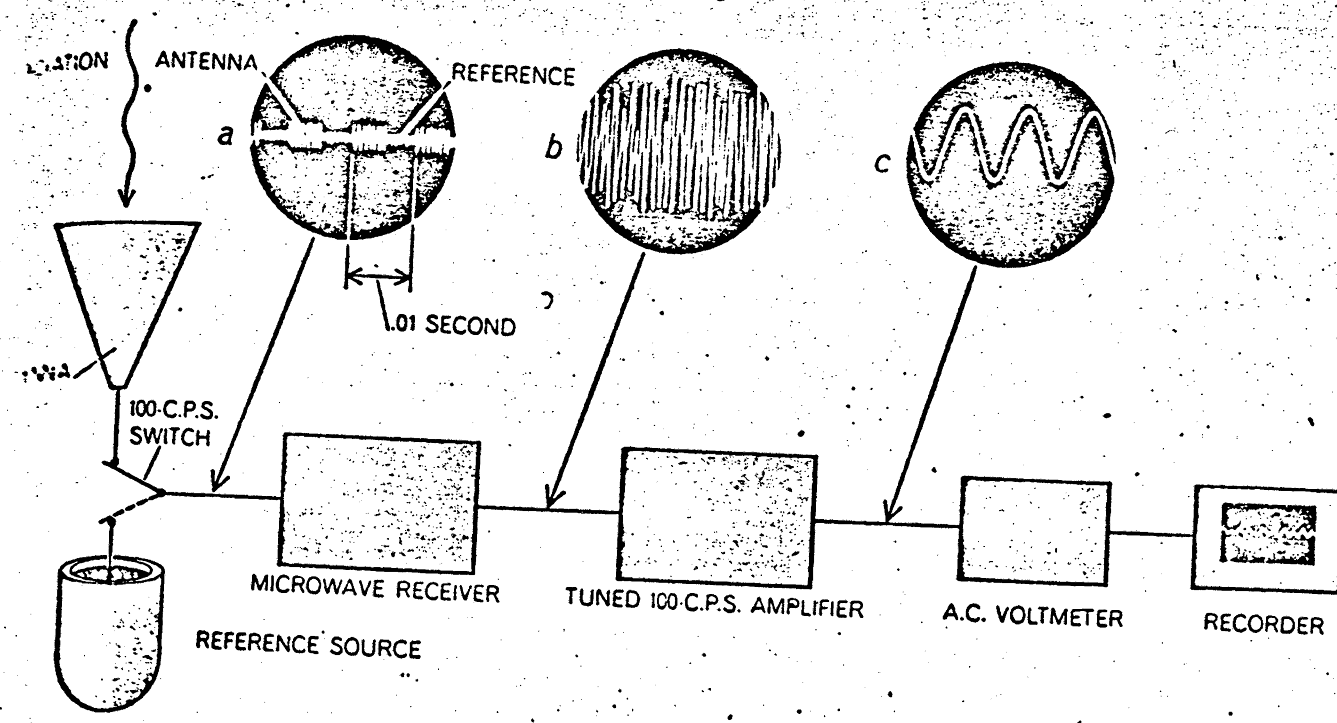
e)

4(a)



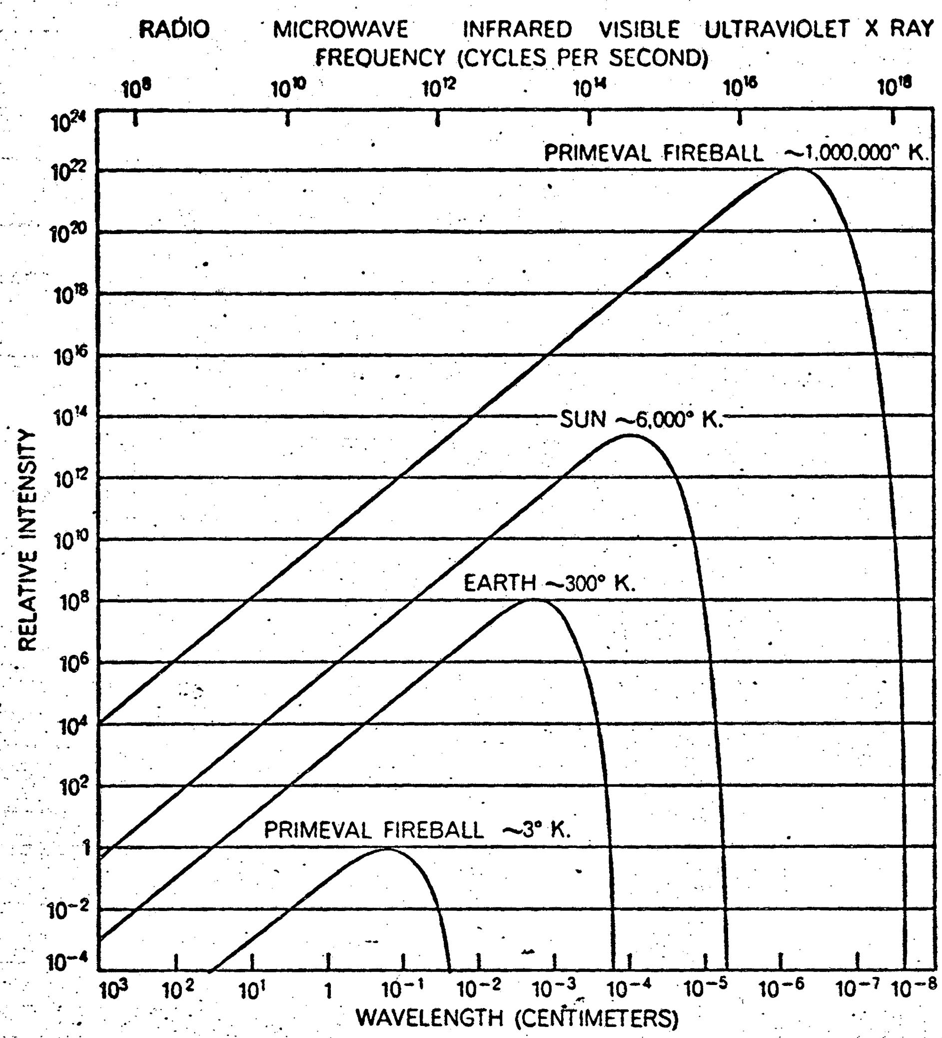
a) THE 1.58 cm. RADIOMETER

Fig 5



General switched radiometer schematic

F/G 2



"BLACK BODY" SOURCES of thermal radiation emit across a broad spectrum, the intensity of the radiation varying with wavelength as shown here for several sources. The shape of the curve persists as its position changes according to the temperature of the source. The top curve is for the fireball radiation billions of years ago, the bottom one for the radiation now.

F/G 3

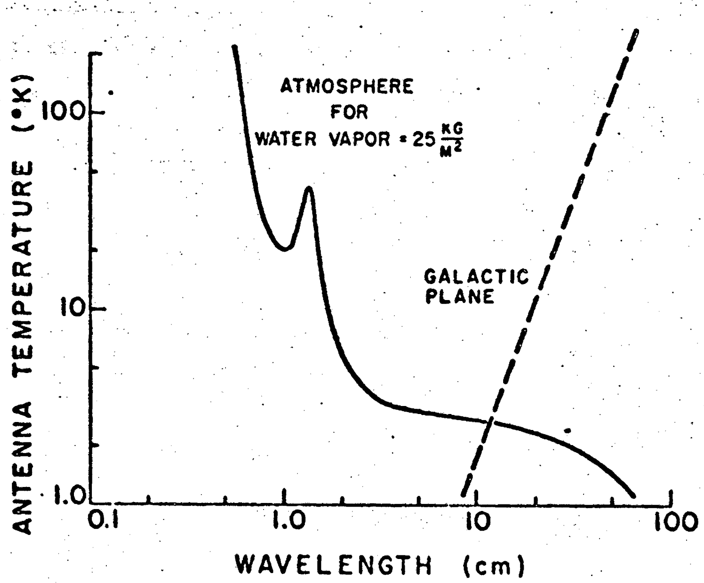


FIG. 2. The spectra of two sources of sky radiation which compete with the cosmic microwave background. Antenna temperature is the thermodynamic temperature of an extended blackbody source which would give an antenna power equal to that being received.

FIG 6 a)

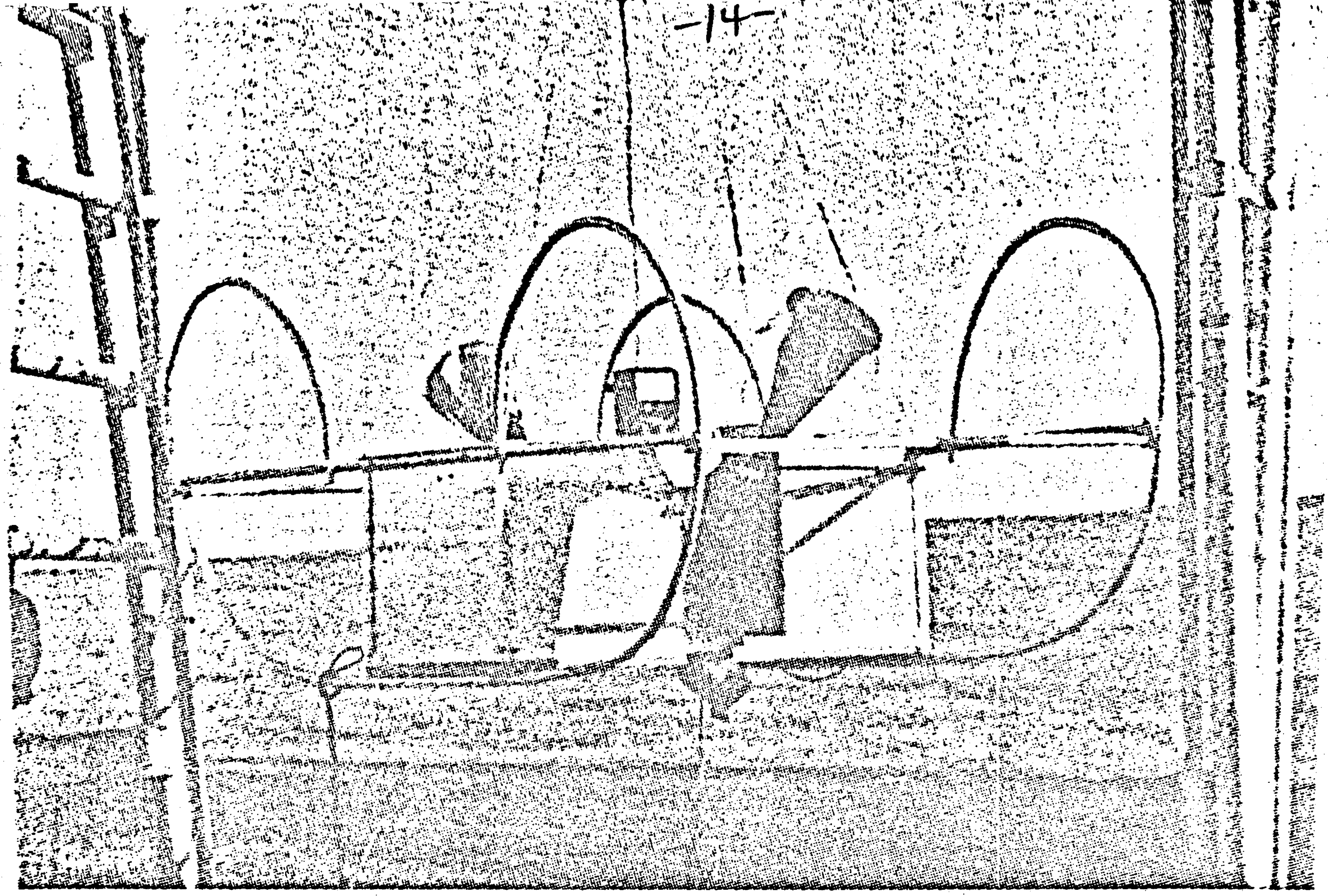
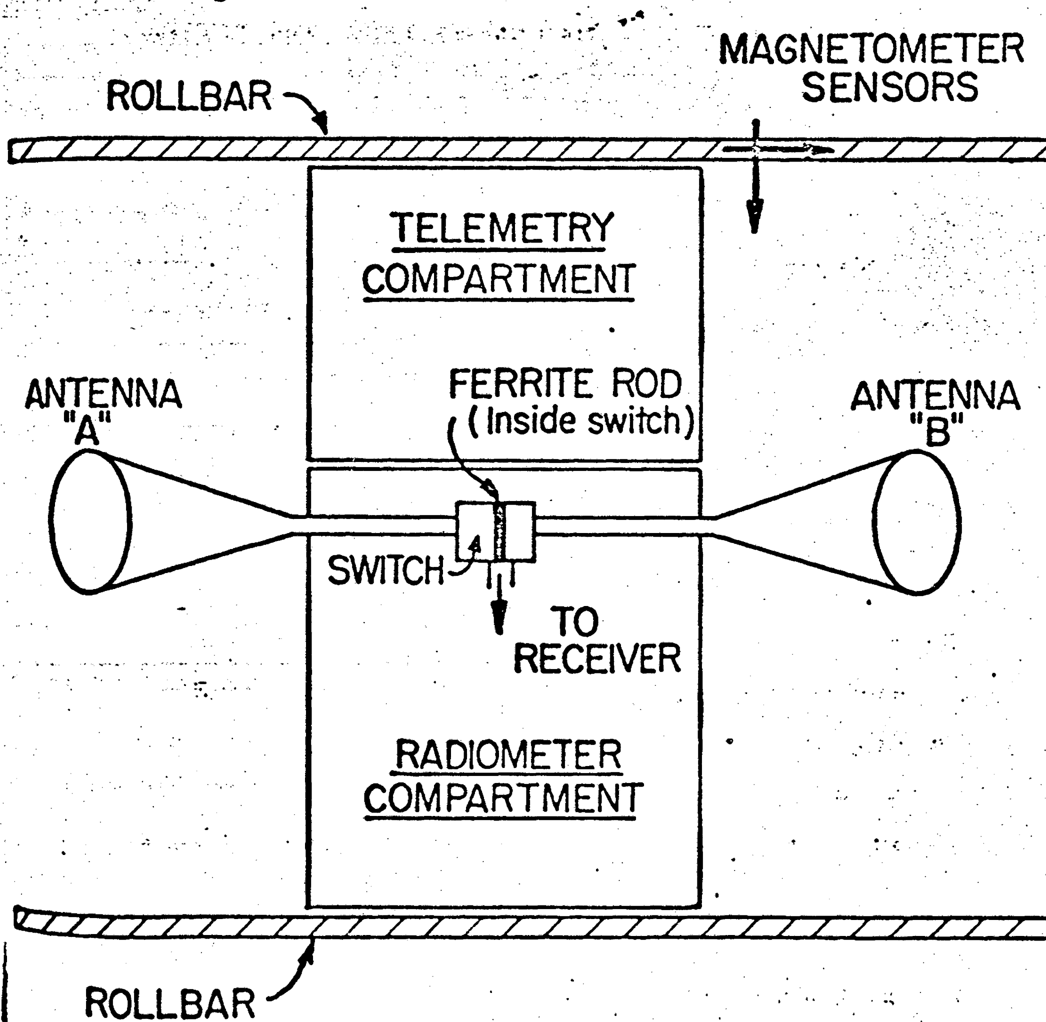


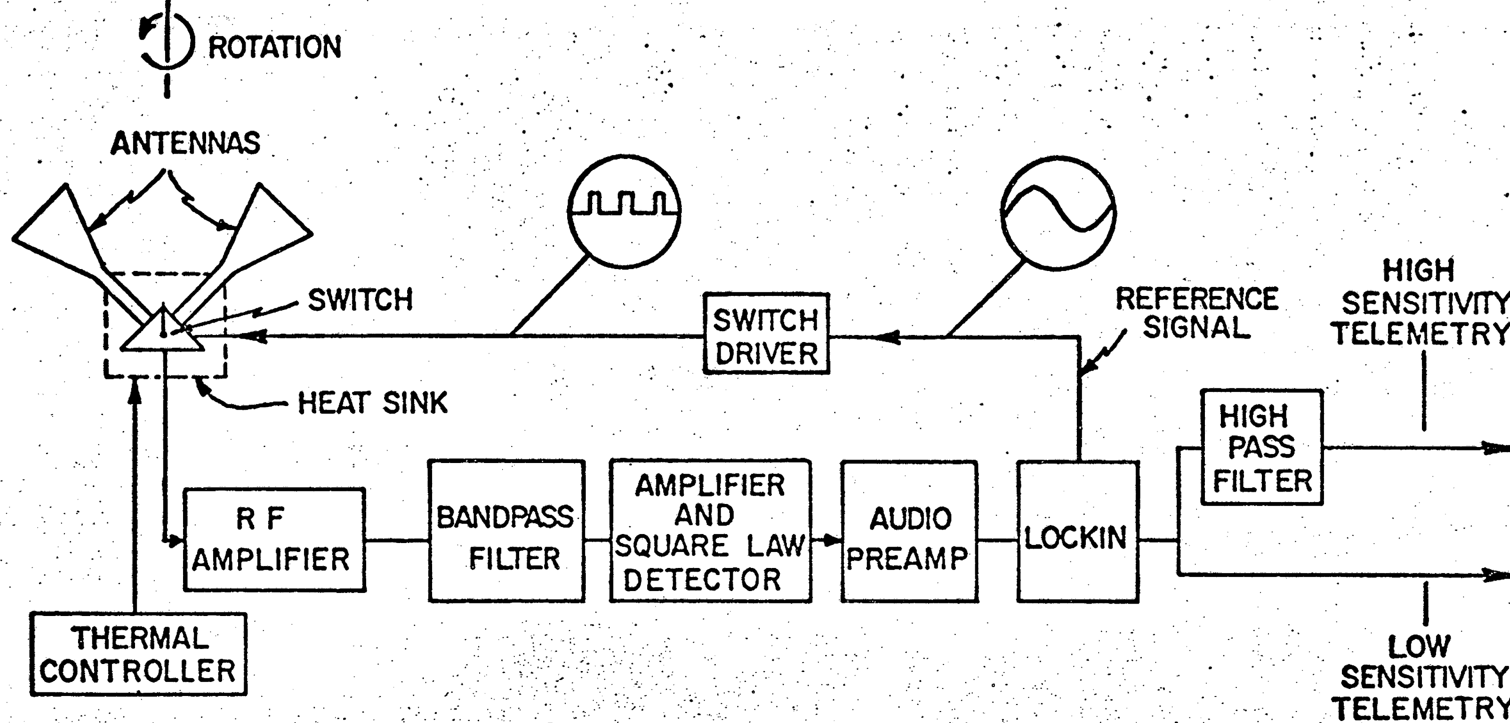
Figure 2.2 Radiometer On Test Stand

b)



THE RADIOMETER

FIG 6a



6(b)

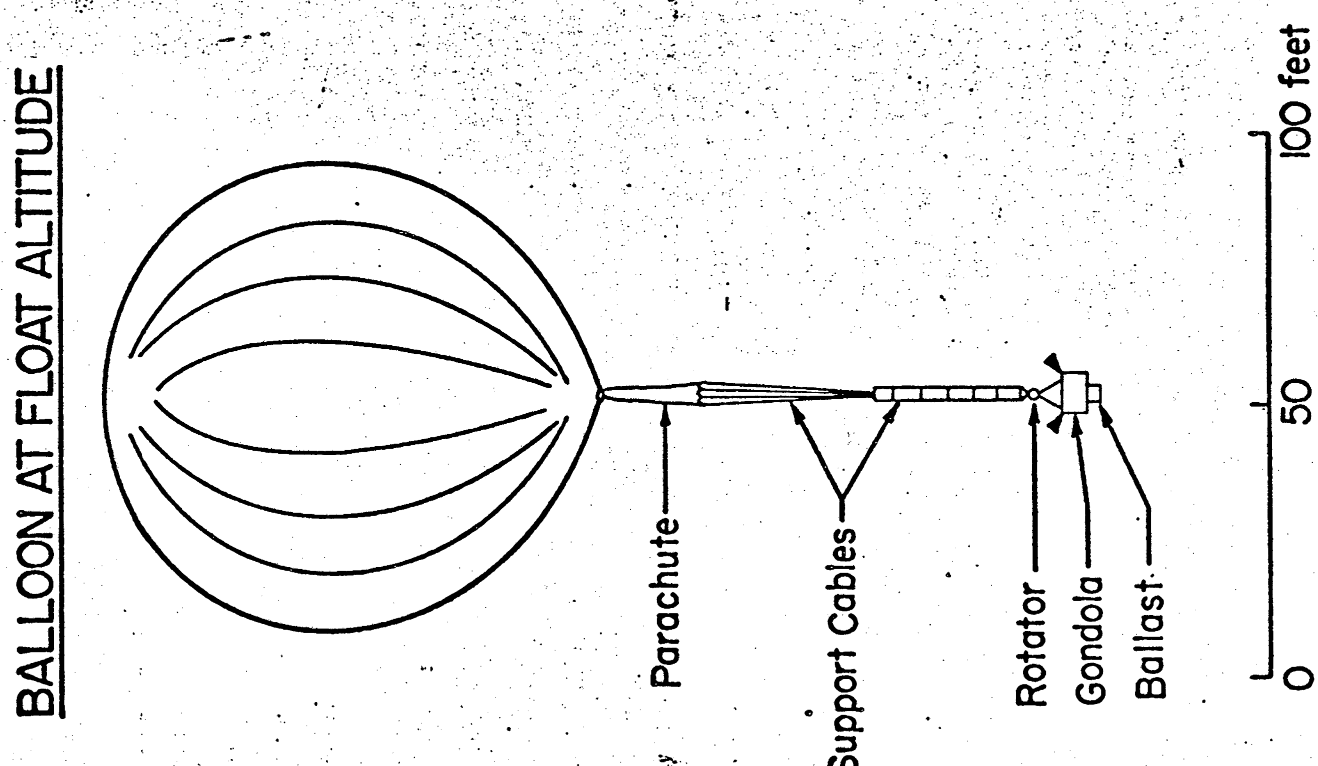


Table 1

Table 15.1 Summary of Measurements of the Background Radiation Flux at Microwave and Far-Infrared Wavelengths.

(The temperatures listed are those for which black-body radiation would give the observed flux at the indicated wavelength.)

λ (cm)	Method	Reference	$T_\gamma(\lambda)$ (°K)
73.5	Ground-based radiometer	a	3.7 ± 1.2
49.2	Ground-based radiometer	a	3.7 ± 1.2
21.0	Ground-based radiometer	b	3.2 ± 1.0
20.7	Ground-based radiometer	c	2.8 ± 0.6
7.35	Ground-based radiometer	d	3.5 ± 1.0
3.2	Ground-based radiometer	e	3.0 ± 0.5
3.2	Ground-based radiometer	f	$2.69\begin{cases}+0.16\\-0.21\end{cases}$
1.58	Ground-based radiometer	f	$2.78\begin{cases}+0.12\\-0.17\end{cases}$
1.50	Ground-based radiometer	g	2.0 ± 0.8
0.924	Ground-based radiometer	h	3.16 ± 0.26
0.856	Ground-based radiometer	i	$2.56\begin{cases}+0.17\\-0.22\end{cases}$
0.82	Ground-based radiometer	j	2.9 ± 0.7
0.358	Ground-based radiometer	j′	2.4 ± 0.7
0.33	Ground-based radiometer	k	$2.46\begin{cases}+0.40\\-0.44\end{cases}$
0.33	Ground-based radiometer	k′	2.61 ± 0.25
0.263	CN ($J = 1/J = 0$)	l	≈ 2.3
0.263	CN ($J = 1/J = 0$)	m	3.22 ± 0.15 ζ Oph 3.0 ± 0.6 ζ Per
0.263	CN ($J = 1/J = 0$)	n	3.75 ± 0.50
0.263	CN ($J = 1/J = 0$)	o	≤ 2.82
0.132	CN ($J = 2/J = 1$)	n	< 7.0
0.132	CN ($J = 2/J = 1$)	o	< 4.74
0.0559	CH	n	< 6.6
0.0559	CH	o	< 5.43
0.0359	CH^+	o	< 8.11
0.04–0.13	Rocket-borne IR telescope	p	$8.3\begin{cases}+2.2\\-1.3\end{cases}$
>0.05	Balloon-borne IR radiometer	q	$\approx 3.6, 5.5, 7.0$
0.6–0.008	Rocket-borne IR radiometer	r	$3.1\begin{cases}+0.5\\-2.0\end{cases}$
0.18–1.0	Balloon-borne IR radiometer	s	$2.7\begin{cases}+0.4\\-0.2\end{cases}$
0.13–1.0	Balloon-borne IR radiometer	s	2.8 ± 0.2
0.09–1.0	Balloon-borne IR radiometer	s	≤ 2.7
0.054–1.0	Balloon-borne IR radiometer	s	≤ 3.4

Table 2

TABLE V-2

POSSIBLE CONTRIBUTIONS TO OUR PECULIAR VELOCITY*

	v_x	v_y	v_z
Rotation (Θ = 250)	123	–113	186
To M31, v = 90	67	12	59
To Virgo, v = 1000ϵ	–970ϵ	–120ϵ	220ϵ

*unit = km sec^{-1}

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historical

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early results

→ For general reading, and further references, see the books by Weinberg & Peebles mentioned on p 1.

Recent discrete source discussion! Rowan-Robinson, MNRAS (1974), 168, 45P.

Recent theoretical & observational situation, see section III, Relic Radiation, IAU Symp. No. 63, Confrontation of Cosmological Theories with Observational Data.