THE DICKE RADIOMETER AND COSMIC RADIATION

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ABSTRACT

R. H. Dicke initiated microwave radiometry in 1946 by inventing the instrument that still bears his name. Eighteen years later he initiated an important sub-field of cosmology by proposing that the universe is filled with microwave blackbody radiation left over from the Big Bang. The Dicke radiometer is widely used to check his idea and to learn new things about the early universe.

THE INVENTION

Dicke's classic paper, "The Measurement of Thermal Radiation at Microwave Frequencies" (1) grew out of his work on radar at M.I.T. Radiation Laboratory. Receiver noise temperature was thousands of degrees in those days, but by rapidly switching the input between the antenna and a reference load he was able to compare their temperatures to an accuracy of a fraction of a degree. As we all know, the trick was wide bandwidth, BW, ahead of the detector and exceedingly narrow bandwidth after, accomplished with a lockin amplifier (tuned to the switch) and a long integration time, t. Dicke worked out the famous radiometer equation for estimating the r.m.s. noise of the output

$$\Delta T_{rms} = T_{System}(BW \times t)^{-1/2}$$

The Dicke radiometer played an important role in launching the new, and extremely productive, field of radio astronomy.

Dicke and his colleagues went on to apply the radiometer to several observations, such as measuring the microwave temperatures of the sun and moon, and mapping the Boston skyline from atop an M.I.T. building (see Figure 1). To investigate the mysterious problem of atmospheric absorption near λ = 1 cm, they took the radiometer to Florida (for humid air) and did tipping runs to measure atmospheric emission (2). A byproduct of those measurements was an upper limit of 20 K on the temperature of any isotropic cosmic background radiation -- a result that Dicke had forgotten 20 years later when he thought about this again in a different context.

COSMIC BACKGROUND RADIATION

By 1963 Dicke's interests had turned to gravitation and cosmology. In thinking about the oscillating universe -- a popular model in those days -- he reasoned that the temperature of the early, compact universe must be very high, 10^9 to 10^{10} K, in order to break down heavy nuclei left over from the previous cycle. (Nuclei heavier than helium are made in stars and supernovae, so they build up during the previous expansion and contraction.) The radiation associated with that high temperature would still be around, he found, but drastically cooled and redshifted by the universal expansion between the hot phase and now. Indeed, the radiation should be in the microwave bands now, and by wonderful conincidence, the Dicke radiometer was just the instrument to look for this "Cosmic Microwave Background."

An instrument (Figure 2) was built at X-band because parts were cheap and atmospheric emission was small, about 3 K. A cold reference load was needed for absolute calibration, and the horn antenna needed to be well shielded from the ground. The whole apparatus tipped away from the vertical to measure and remove atmospheric radiation. Before the experiment was ready, Penzias and Wilson reported "A Measurement of Excess Antenna Temperature at 4080 Mc/s," discovering the Cosmic Background (3). Dicke's idea seemed to be the best explanation for the excess radiation in their large horn antenna at Holmdel (4). Penzias had built a cold reference load to better understand their radiometer.

It turns out that at the same time Dicke was inventing the microwave radiometer, Gamow was thinking about blackbody radiation from the Big Bang (5). He and his colleagues were trying to produce heavy nuclei in the Big Bang and found a byproduct of radiation which they calculated would still be around today with a temperature of 5 K, or so. Recall that Dicke was trying to destroy heavy elements, but reached the same conclusion.

Fig. 1. Dicke shakes the "Shaggy Dog" calibrator in front of the 1 cm radiometer used to measure atmospheric absorption. Also in the picture: E. Beringer, R. Kyhl and A. Vane.

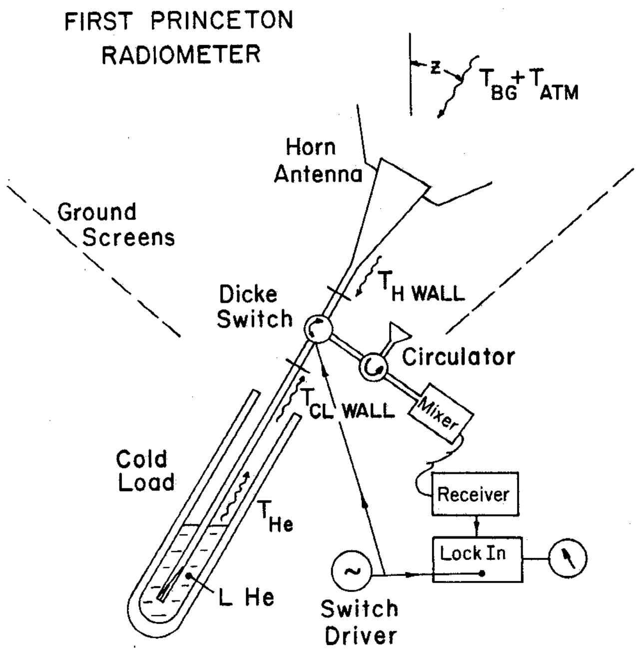

Fig. 2. The Princeton 3 cm radiometer. The switch connections could be reversed to measure and remove its offset.

MODERN METHODS

Tracing out the spectrum -- predicted to be a blackbody -- has been the primary test of the supposed cosmic origin of the microwave background radiation. Radiometers and techniques have evolved over the years, cluminating in the beautiful results from the COBE satellite (6) for wavelengths shorter than 1 cm. For longer wavelengths the best measurements are still ground-based (7), limited mainly by errors in measuring the atmospheric emission. An important step in the evolution of cosmic background radiometers at Princeton is shown in Figure 3. The radiometer looks down at the sky reflected by a large mirror, so that the instrument does not have to be moved to look at the cold load, as shown. Insertion losses and switch asymmetry are cancelled by attaching the cold load to the horn antenna. Measurements were made at White Mountain at three wavelengths (8).

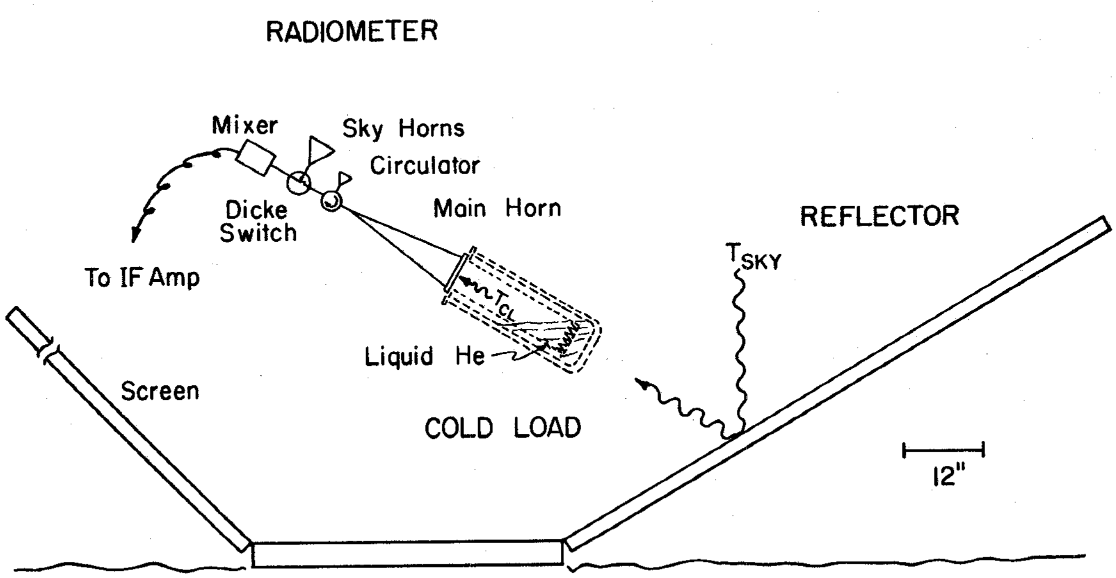

Fig. 3. The method used for three radiometers, λ = 3.2, 1.58 and 0.86 cm. The results fit a blackbody spectrum and gave a radiation temperature of 2.68 + 0.09 - 0.14 K.

The future of cosmic background measurements for wavelengths between 1 cm and 10 cm is indicated by a 1% measurement from a balloon (9). The radiometer is shown in Figure 4. Residual atmospheric radiation is only a few x 10^{-3} K, and the instrument front end is isolated and operated at 2.7 K -- close to the temperature of the incoming radiation. This is an important point as effects of insertion loss and reflections are greatly reduced. The horn throat is separated, and the calibration load (also near 2.7 K) is moved to establish the radiometer's zero point.

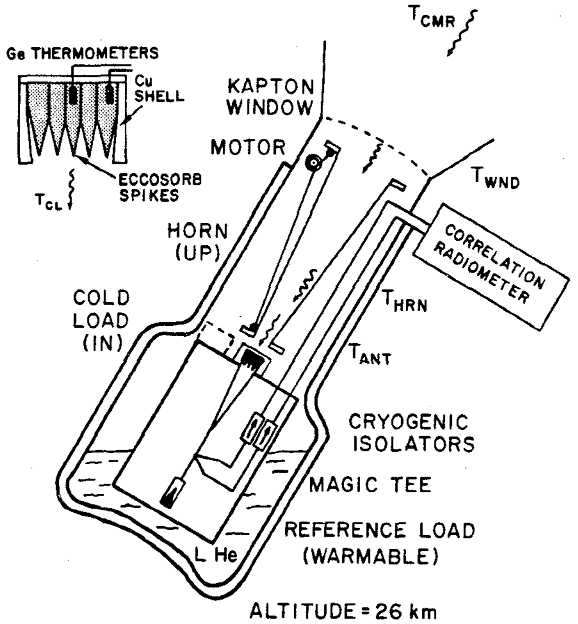

Fig. 4. A balloon-borne radiometer designed to have critical front-end components in thermal equilibrium with the incoming radiation. Using a correlation radiometer allowed us to use existing, room temperature, mixers. Now, cryogenic rf amplifiers are being used.

At wavelengths longer than 10 cm Galactic radio emission becomes a problem and the horn antennas become large. Ground-based instruments are still indicated, and better measurements are badly needed. But again here, radiometers with front-ends near the measured radiation temperature have many advantages (10).

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