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Author
Smoot, G.F.

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Lawrence Berkeley Laboratory

UNIVERSITY OF CALIFORNIA

Physics Division

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THE SPECTRUM OF THE COSMIC BACKGROUND RADIATION:
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MOUNTAIN RESEARCH STATION

G.F. Smoot

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The Spectrum of the Cosmic Background Radiation: Early and Recent Measurements from the White Mountain Research Station

GEORGE F. SMOOT

Space Sciences Laboratory & Lawrence Berkeley Laboratory,
University of California, Berkeley

The White Mountain Research Station has provided a support facility at a high, dry, radio-quiet site for measurements that have established the blackbody character of the cosmic microwave background radiation. This finding has confirmed the interpretation of the radiation as a relic of the primeval fireball and helped to establish the hot Big Bang theory as the standard cosmological model.

1. INTRODUCTION

The popular idea that the universe began with a Big Bang can trace its roots to the discovery of the cosmic background radiation (CBR) in 1965 by Penzias and Wilson. The CBR was immediately interpreted [*Dicke et al.*, 1965] as a remnant of the primeval explosion. Its discovery is the major reason that the Steady State theory of the universe lost favor, while the Big Bang theory has steadily advanced to dominance. The Big Bang theory, as originally worked out by Alpher, Herman, and Gamow [*Alpher, Bethe, and Gamow*, 1948; *Alpher*, 1948; *Alpher and Herman*, 1948; *Gamow*, 1948; *Gamow*, 1956], correctly predicted both the existence and the approximate intensity of the CBR twenty years before its discovery while competing theories had no clear explanation for its existence.

According to the Big Bang theory, the universe is expanding from an incredibly hot and dense condition. We see evidence of that initial expansion in the recession of distant galaxies as first measured by *Hubble* [1937]. All galaxies appear to be moving away from all other galaxies at a rate that is proportional to their separation. This is just what we would expect for a uniform expansion of the whole universe. The Big Bang theory predicts that the universe should be about 25% helium by weight in good agreement with what is thought to be the cosmic abundance. The helium was calculated to have been synthesized about three minutes after the initial Big Bang singularity, a time when the temperature of the universe would be billions of degrees. As the universe expanded it cooled. At about 10^5 years, it reached the temperature of the sun's surface (about 3000 K) and the universe became much less opaque to light, effectively transparent, as the primordial plasma combined to form neutral atoms (mostly hydrogen and helium). The light from that epoch has traveled to us undisturbed for about 15 billion years. The general thousandfold expansion of the universe since that time has cooled that radiation to a temperature of about 3 K. The cosmic background radiation is the present relic of that primordial light.

The Big Bang theory predicts that the cosmic background radiation should be isotropic, unpolarized and have the spectrum given by a blackbody (perfectly absorbing) object. A distinctive property of a blackbody spectrum is that it is characterized by a single parameter—its temperature T_0. If we know the temperature of the blackbody, we know the intensity of the radiation at every wavelength or frequency. Figure 1 shows examples of three different blackbody spectra. Note that at each frequency each spectrum has a different and particular value.

Penzias and Wilson [1965], working at Bell Laboratories in New Jersey, measured and published a value of 3.5 ± 1.0 K for the temperature of the cosmic background radiation at a wavelength of 7.35 cm. This result was the discovery of the CBR. Shortly after that the Princeton group made a measurement and found a value of 3.0 ± 0.5 K at a wavelength of 3 cm [*Roll and Wilkinson,* 1966]. Because they recognized the importance of the discovery and the need for confirmation and testing of whether the spectrum had a blackbody spectrum, several groups immediately set out to measure the spectrum at new frequencies and greater accuracies. It was quickly realized that better sites would be needed to make more accurate measurements. At this point White Mountain became a major site for measuring the spectrum of the cosmic background radiation. Groups from Berkeley, MIT, Princeton, and Aerospace Corporation set up experiments there and began observations. These early experiments were primarily using White Mountain as a high dry site. Appreciation for its remoteness and relative isolation from man-made interference was barely developing.

The early experiments were simple in concept just as these experiments are today. Each CBR measurement compares the power received while pointing the instrument at the zenith with that received while pointing at an absolute reference blackbody load. Radiation reaching a radiometer pointing at the zenith comes from a number of sources: the CBR, the atmosphere, the galaxy, and the ground. The aim of the experiment is to measure the difference in power between the zenith and the reference load accurately and then account for all the sources of radiation so that the residual excess is the CBR. The atmosphere is typically one of the most significant sources of power. Its emission is usually measured by observing the sky at different zenith angles so that the amount of atmosphere observed is varied.

A typical radiometer is made of a receiver and antenna and signal processing electronics. The antenna can view either the absolute-temperature reference load or the sky at various angles from the zenith.

2. The Early Experiments

The First Berkeley Group

The first group to arrive at White Mountain looking for a place to make CBR measurements was, naturally enough, the radio astronomy group from Berkeley. A quick reconnaissance trip was made by Jack Welch, Dave Cudaback, and Doug Thornton. They flew by small plane to Bishop and by helicopter to Barcroft. In spite of afternoon dizziness, general altitude adjustment problems and clinical discussions by the medical researchers during dinner, Barcroft was found to be a potentially suitable site. The radio astronomy group set up their equipment in a trailer, tested it in Berkeley and hauled it up to White Mountain in the summer of 1966. They stayed in the old Barcroft building on and off for several weeks. At night one person sat on the roof of the trailer tipping the antenna to different angles while one person stayed inside the trailer recording the date. Often the person on the roof was graduate student Gerry Wrixon who used Irish coffee to buffer against the winds and 0° C temperature.

Even with these various problems and handicaps the Berkeley group measurements showed agreement with the CBR hypothesis at temperature of 2.0 ± 0.8 K at 1.5 cm wavelength [*Welch et al.,* 1967] and established White Mountain as a good site.

The MIT Group

In June and July, 1967 a group from MIT consisting of Professors Bernard F. Burke and David H. Staelin, aided by D. Cosmo Papa, Eugene Papa, and graduate student Martin S. Ewing measured the newly discovered 3 K isotropic cosmic background radiation at 9 mm wavelength. Dave Staelin gave this brief description of the MIT experiment. "We arrived at the Barcroft site shortly after the roads had been plowed open for the first time that spring, and were impressed by the enormous snow banks that bounded them. Our first task after arriving at the site was to dig trenches that could drain the flat area where we were to operate our equipment. We also had to dispossess several families of mice occupying drawers in our desk like a miniature condominium.

After a few days of acclimatization to the altitude everything proceeded smoothly, yielding the desired confirmation of the isotropic background radiation at our shorter wavelength. The extremely low levels of precipitable water above the site made it ideal for these purposes."

The results of 3.1 ± 0.26 K [*Ewing, Burke, and Staelin,* 1967]. supported the hypothesis that this radiation had an isotropic blackbody character at this wavelength, consistent with previous measurements at longer wavelengths.

The Princeton Group

The Princeton group [*Stokes, Partridge, and Wilkinson,* 1967] also abandoned New Jersey as an observation site and came to White Mountain in the summer (July and August) of 1967 with radiometers operating at wavelengths of 0.856, 1.58, and 3.2 cm. These represented a second generation of experiments—with some subtle but important refinements over the previous measurements.

Dave Wilkinson described his auspicious meeting with Nello Pace, the founder and director of the laboratory: "I was going down the mountain from Barcroft on a Honda 90 motorscooter when I met this man whose large four wheel drive vehicle was mired axle deep in mud. Several people were trying, with great difficulty, to free it. I tactfully suggested he change vehicles since he had not yet seen the worst of the mud. He did not accept this advice gracefully. Later when we discovered each other's identity, Nello Pace and the crew were courteous and helpful to us.

We were surprised to meet the MIT group at Barcroft. There were only two groups trying to make measurements at the 9 mm wavelength range. Unknown to each other, we arrived at White Mountain almost simultaneously. We made an agreement not to tell each other the results even though we could see each others' equipment and watch each other working." This was important scientifically in order to maintain the independence of the experiments and results, since one can get a reasonable good estimate of the experimental results while conducting the experiment.

Simple calculation would be accurate to about 10%. The Princeton group measured cosmic background temperature of 2.7 ± 0.2 K, 2.8 ± 0.15, and 2.56 ± 0.18 for wavelengths of 3.2, 1.6 and 0.9 cm respectively. These measurements confirmed and improved our previous results. They firmly verified that the background radiation followed the blackbody spectrum at long wavelengths.

The Aerospace Corporation Group

With the several measurements in the Rayleigh-Jeans regions showing evidence of a 3 K background radiation, attention moved towards detecting the turn down at the peak both to test that it was truly a blackbody with the proper Wien cutoff and to put an upper limit on the total allowed flux. Because the atmosphere is so opaque at these higher frequencies experimenters tried to make measurements with instruments carried aboard rockets and balloons. Unfortunately, they seemed to find fluxes much higher than would come from a 3 K background radiation.

In October 1969, a group of researchers from the Aerospace Corporation [*Millea et al.,* 1971] came up to the Crooked Creek station from Los Angeles to make observations. Their motivation was to check that the spectrum was indeed blackbody and not a thermal source that was partially opaque. At long wavelengths (in the Rayleigh-Jeans region) the spectral intensity from a blackbody increases as the square of the observation frequency. However, a 2.7 K blackbody should peak at a wavelength of about 1.6 mm and the flux should decrease very quickly for shorter wavelengths. They chose a wavelength of 3.3 mm where the flux should be one third of the Rayleigh-Jeans extrapolated value. This wavelength had been previously measured by the Princeton group with relatively little data from Climax, Colorado. In the meantime, other groups had reported excessive values at higher frequencies. The Aerospace group confirmed and improved the Princeton results.

The Second Berkeley Group

With the Princeton and Aerospace as well as observations of interstellar CN and CH molecules supporting the 2.7 K blackbody hypothesis at wavelengths longer than about 3 mm, and with balloons and rockets reporting excess flux at shorter wavelengths, a conflict existed. Searches were made for spectral features in this short wavelength band; one group reported detecting a strong emission feature in the 1 mm wavelength region.

When these results were reported, once again a Berkeley group, this time consisting of Prof. Paul Richards, graduate student John Mather, and Michael Werner, a post doc with Prof. Townes, turned to White Mountain as a place to check these results [*Mather, Werner, and Richards,* 1971].

This Berkeley group again flew up in a helicopter and experienced the usual acclimatization problems such as a decreased IQ. Mather reports he was impressed to see Professor Richards being so remarkably blue-colored when he got off the helicopter. At least they were wise enough to have learned about working conditions and knocked out a window pane to stick the light gathering pipe out the window so that they did not have to be out in the cold wind at night. They remember the old eggs saved from the high altitude chicken experiment as well as helping to shovel snow into the melters to get water as being an integral part of the experimental process. Mather remembers the helicopter rides most vividly—especially those down from the mountain. Since the helicopter did not have enough lift when he was jammed aboard with the cryogenic tanks, the helicopter just dove down the mountainside.

On April 27 and May 3, 1971, using a Fabry-Perot spectrometer with high spectral resolution, Mather *et al.* looked for any high altitude atmosphere feature or other factor that could have caused this high flux and found no evidence for this excess flux. This effort stimulated them to begin a program to measure the high frequency portion of the CBR spectrum which eventually used balloons and rockets and is still underway.

3. Recent CBR Spectrum Measurements at White Mountain

In 1980, my group in collaboration with groups from Milan, Bologna, Padova, and Haverford College began a program to measure the low-frequency spectrum of the CBR. In the summers of 1980 and 1981, we went to the Barcroft Laboratory to evaluate the site and test various pieces of equipment. While much of the physical plant had improved, to our dismay we found the electrical power lines were down and we had to rely on generators and batteries to run the equipment. In June of 1982, the full collaboration and equipment converged in Berkeley to test the instruments and to organize for the experiment. The entire group then packed up the various pieces of equipment into four different trucks, packed the people into cars and caravaned to White Mountain. We had our difficulties getting all the equipment up the mountain including a significant brush with snow on Sheep Mountain.

We surveyed the area around Barcroft laboratory, made some test holes and finally built and dedicated the "White Mountain Shortline Railroad." We unloaded the rest of our equipment and put the carts on the rails. We had an extensive period of testing, interrupted by a large snow storm at the beginning of July, to make sure equipment had survived the trip intact. We finally made observations on the 4th of July weekend. The 4th was notable both for a lunar eclipse and for the sight of Jan Hart skiing down Barcroft with a sparkler in each hand during the middle of our run that night. The next year we made observations during Labor day weekend. We had noticed that a lot of man made interference went away on weekends and especially on vacation weekends and fortuitously we were ready and the weather was good on these two national holidays.

Between the 1982 and 1983 observations, the groups took their equipment back to their respective laboratories, modified and improved it, and returned in late August of 1983. In the middle of the run a number of failures coalesced to great chaos and destruction. First we lost a Sola voltage regulator used to condition the power that ran much of our equipment. Then a voltage regulator on a generator failed, and since the other generator was not working properly, a patch repair was applied. Later that night the generator ran away boosting its output voltage to around 180 volts. Amidst much noise, bright lights, sparking, flashing and smoke, a lot of equipment was damaged. Particularly important to us was our computer which had many internal components charred. Much of the other equipment was readily repaired—because of fusing or similar protection. The radiometers were powered from batteries so that they were protected from the worst effects of the power surge. But the lights and other tools were out of commission in the middle of the night and the middle of the run. In order to get parts and help we first had to repair the radio phone and have replacement computer boards rushed to us. In the meantime, we took data by hand and by using a magnetic tape recorder data logger. This effort completed the data taking by the full collaboration. The results from the collaboration are summarized in a paper by *Smoot et al.* [1985].

My group returned in August 1984 with a new radiometer designed to make measurements at many frequencies. Due to unusually poor weather and other problems we did not obtain much good data for the 1984 trip. We have thus planned to modify and improve our equipment further and return when good weather and power prevail. (We have also been waiting for a part that is now six months late in delivery.) We plan to investigate the suitability of the site for continued observation of the CBR.

4. Results

The measured atmospheric emission and our model of atmospheric emission are shown in Figure 2. The results of the measured thermodynamic CBR temperature are listed in Table 1 and shown in Figure 3. The White Mountain data alone as well as all the world's measured data are consistent with a blackbody spectrum with a temperature of $T_{CBR} = 2.72 \pm 0.03$ K. A fit of all the data to a blackbody spectrum plus a small distortion indicate that the largest distortion allowed is about 6% [*De Amici et al.,* 1985]. By considering various scenarios for the evolution of the universe using the Big Bang model we can derive limits on the energy release over the lifetime of the universe. Figure 4 shows an example of typical limits derived in this manner. This in turn allows us to place limits on the possible processes that could have occurred in the early universe. As an example, we can rule out the scenario that galaxies and clusters of galaxies formed as a result of large scale primordial turbulence. The bulk motions of matter that would be necessary would have distorted the spectrum by more than is allowed.

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G. F. Smoot, Bldg. 50, Rm. 232, Lawrence Berkeley Laboratory, University of California, Berkeley, CA 94720.

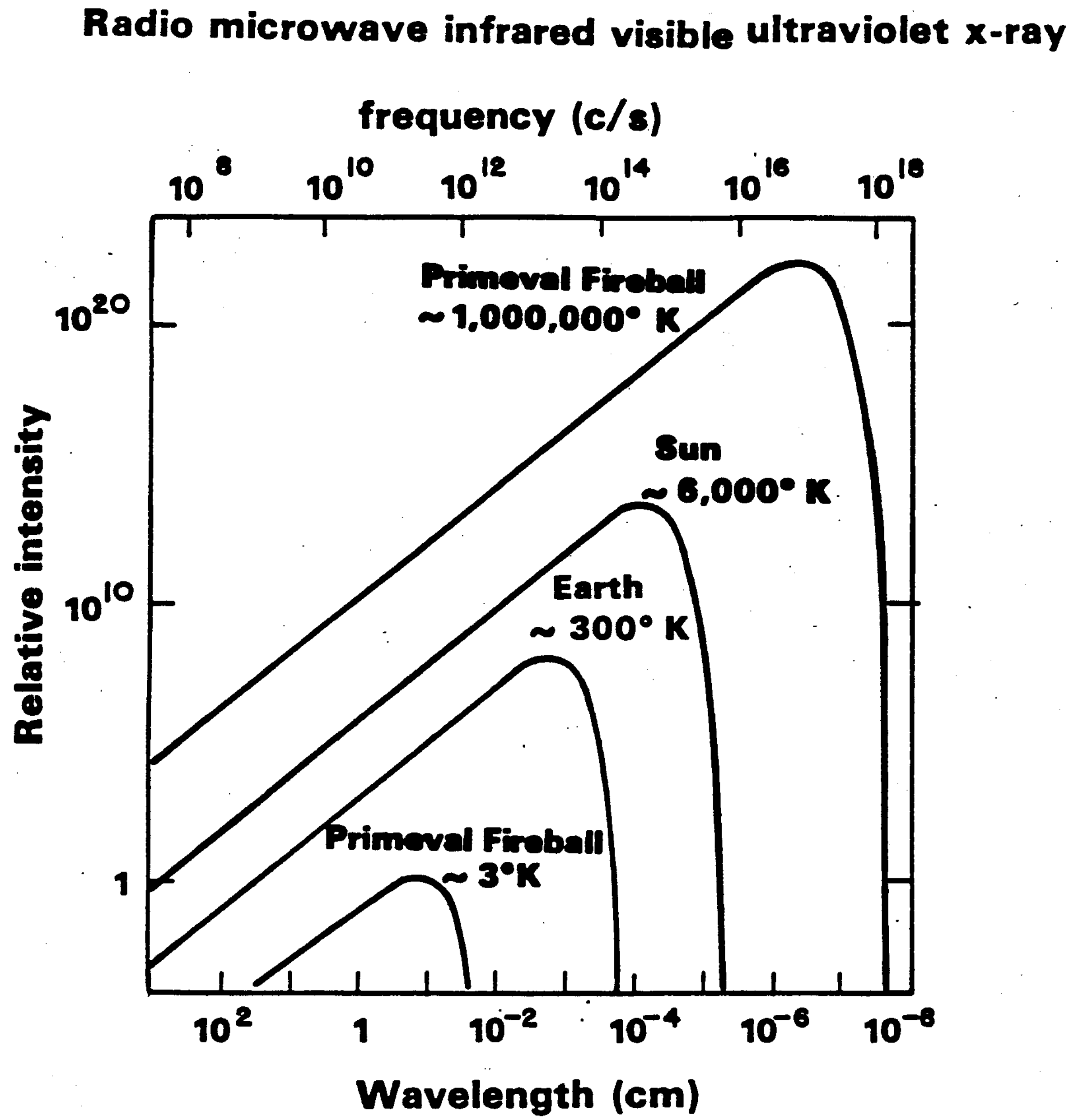

Figure 1: Curves of intensity of radiation versus wavelength (or frequency) for four sample blackbody temperatures.

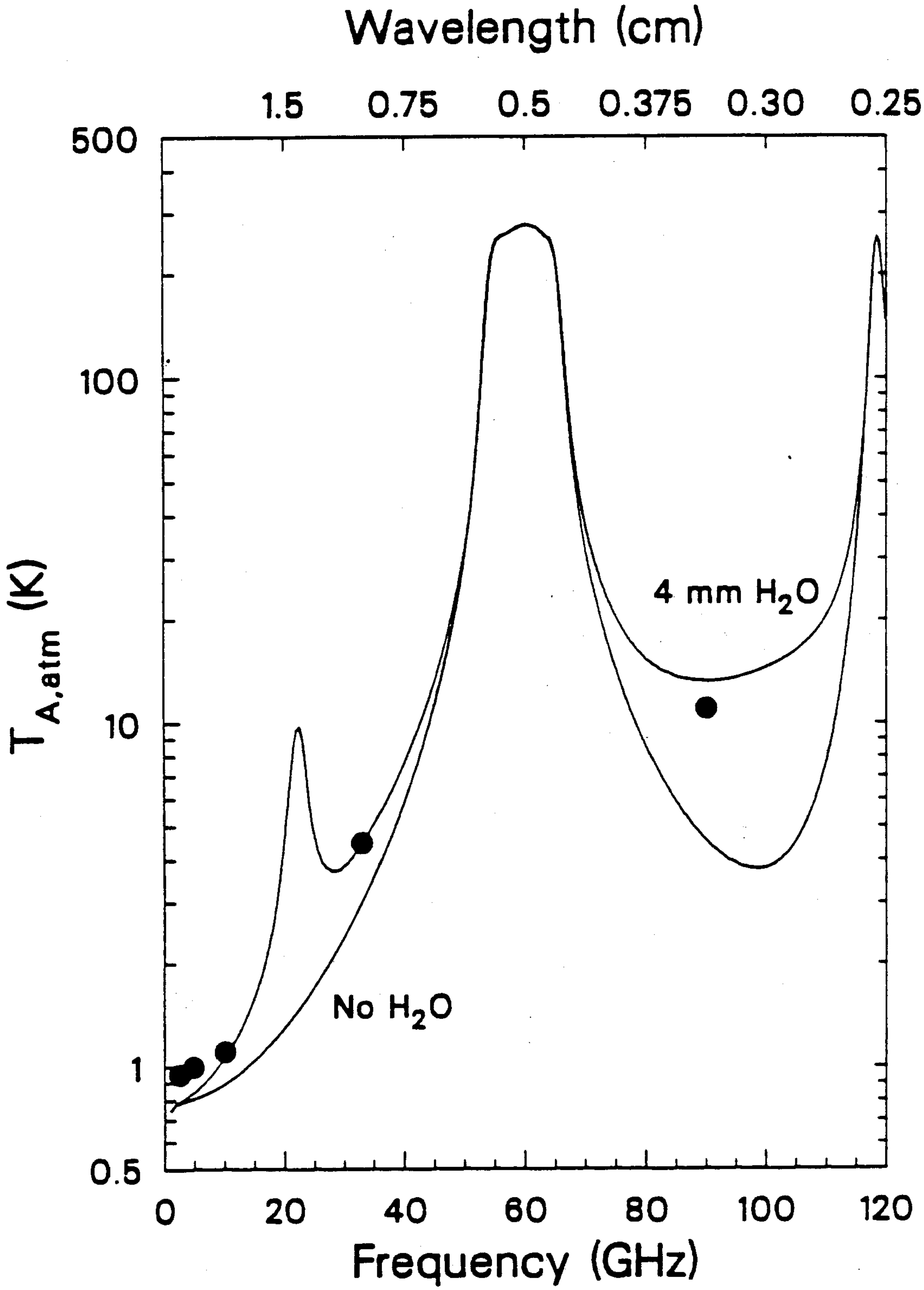

Figure 2: Measured and calculated atmospheric emission at 3800 m altitude of the White Mountain Research Station at Barcroft. Plotted points are our typical measurement values.

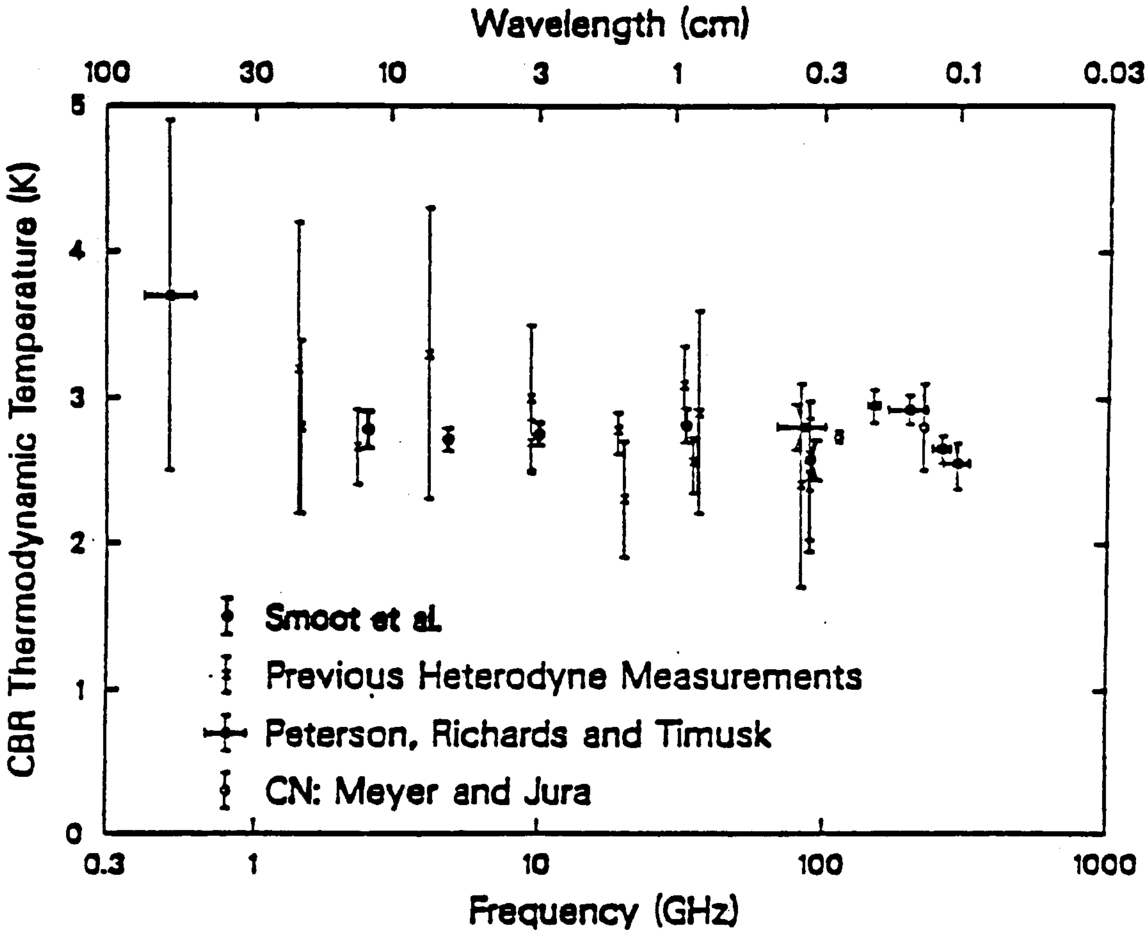

Figure 3: Current Cosmic Background Radiation Temperature Measurements.

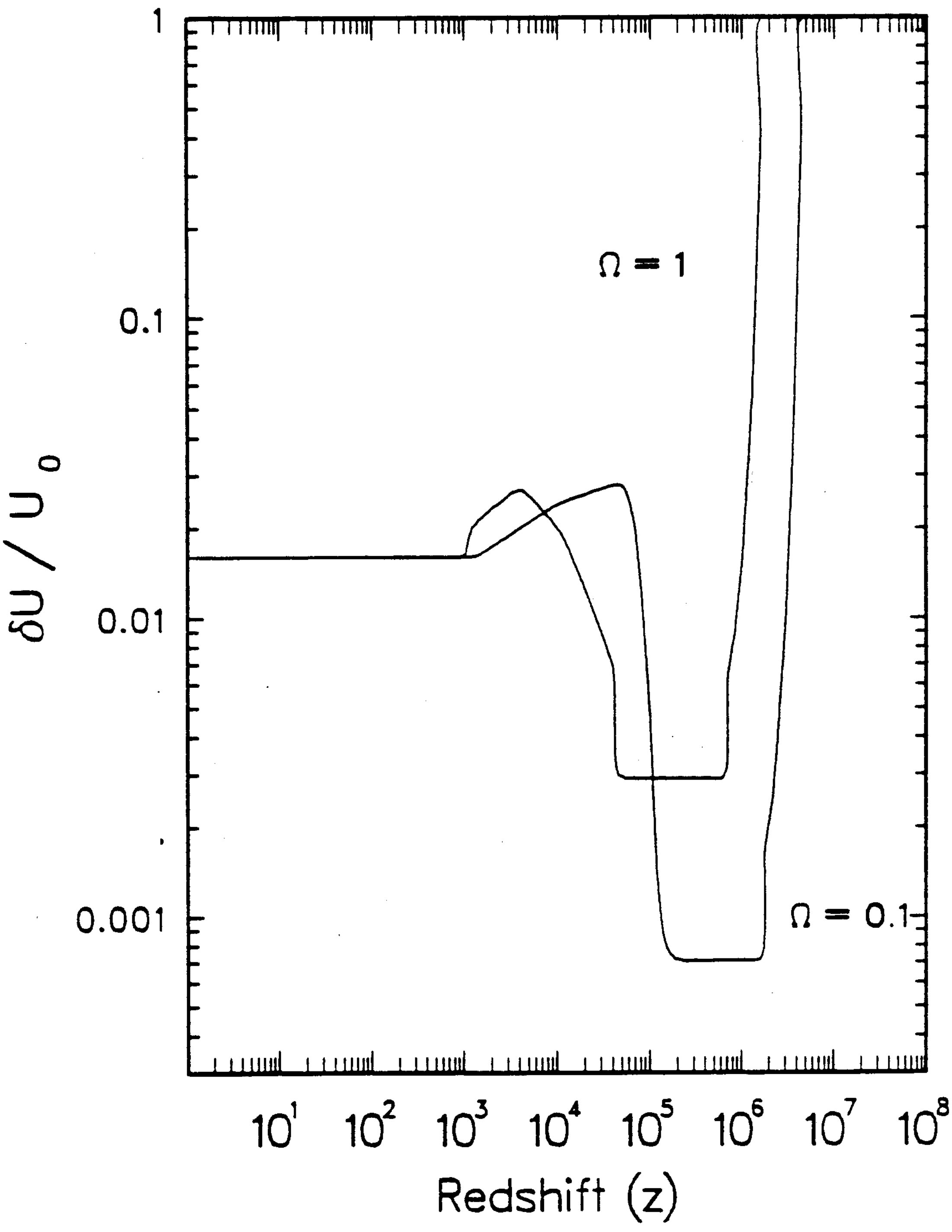

Figure 4: Limits on the fractional energy added to the CBR as a function of redshift (inverse of the size of the expanding universe).