COMMENTS AND SUMMARY ON THE COSMIC BACKGROUND RADIATION

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This session on the cosmic background radiation is remarkable for the quality of the interesting new results presented and the controversy over substantive issues. This paper reviews the status of measurements of the spectrum and anisotropy of the cosmic background and summarizes what is known of the properties of the cosmic background radiation: its spectrum, anisotropy, polarization, and statistics.

SPECTRUM

I would like to comment on the spectrum of the cosmic background radiation, the one area where no direct new experimental data was contributed. There are two experiments with results pending: (1) a repeat measurement with new detectors planned by Richards' group and (2) the low frequency measurement whose first phase we have just concluded. Figure 1 shows the currently published spectrum measurements with arrows indicating the five low frequencies at which we have just made measurements and the five high frequencies Richards' group plans to measure.

These low frequency measurements were a collaborative effort with G. Sironi from Milano responsible for the 12 cm radiometer, N. Mandolesi of Bologna responsible for the 6 cm radiometer, and B. Partridge of Haverford College responsible for the 3.2 cm atmospheric monitor. My group from UC Berkeley was responsible for the cold-load calibrator, the support system, and the three higher-frequency radiometers. S. Friedman, G. De Amici, and C. Witebsky were responsible for the 3, 0.9, and 0.33 cm wavelength radiometers respectively.

After a full test at Berkeley the experiment was conducted at the UC White Mountain Research Station at a dry (2-3 mm H_2O), high-altitude (3800 m or 12,500 ft) site. The cold-load calibrator was set in the ground, suspended from a railroad. Each spectrum-measuring radiometer was mounted on a cart allowing it to be rolled along the railroad and positioned above the cold-load calibrator. The radiometers measured the emitted power from the cold-load calibrator and then from the sky, each relative to the power entering the reference antenna. By differencing the power measurements and by knowing the temeprature of the cold-load calibrator and the conversion from power to antenna temperature, we determined the temperature of the sky.

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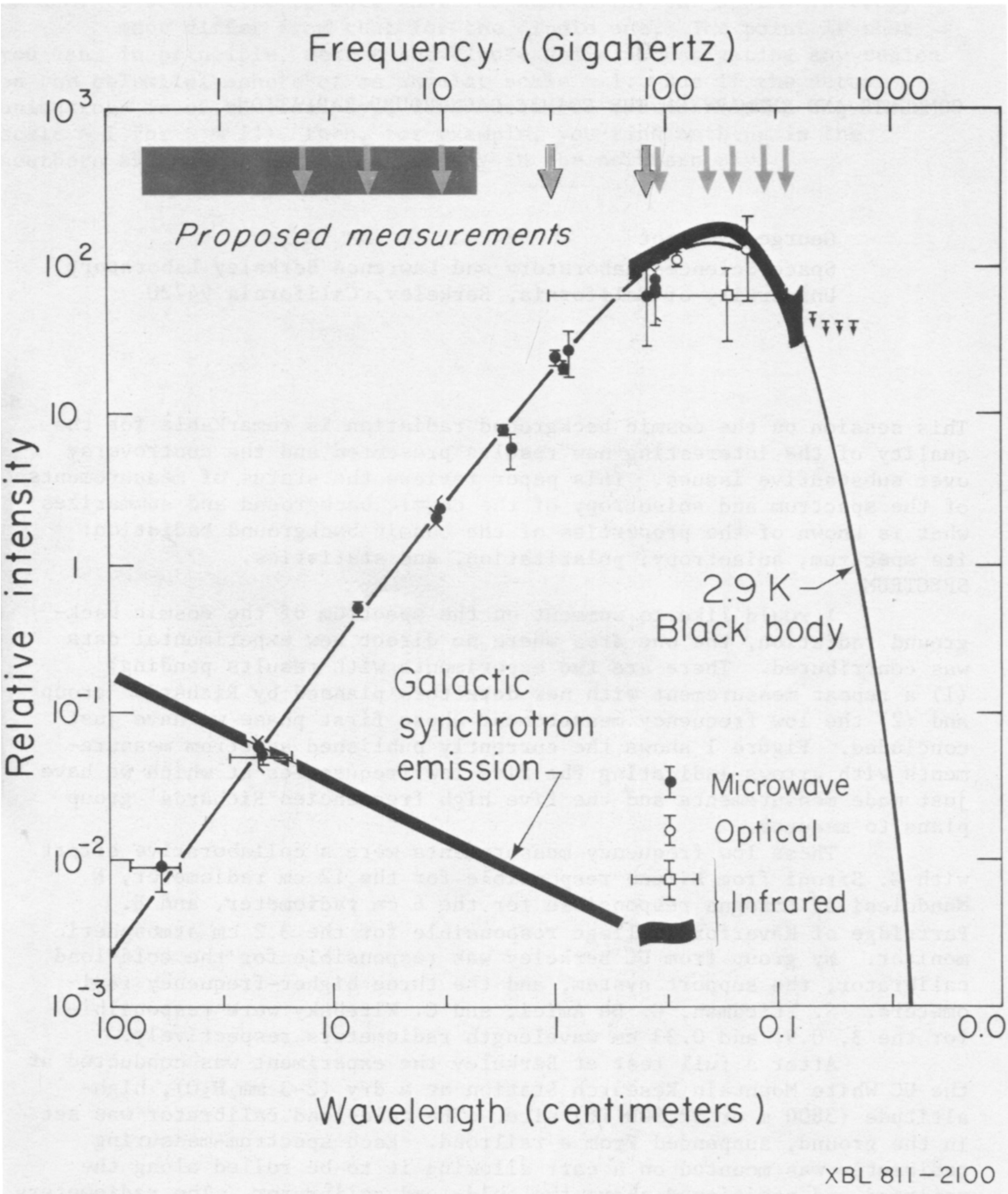

Figure 1: Current and Proposed Measurements of Cosmic Background Radiation Spectrum.

The antenna temperature of the sky is the sum of the cosmic background radiation, galactic emission, atmospheric emission, and emission from the earth and surrounding objects. The emission from the atmosphere was determined through zenith scans. Low-sidelobe antennas and ground shields reduced pickup of emission from the earth to negligible levels. At the lowest frequency the minimum galactic emission gives 0.2 to 0.3 K of antenna temperature and decreases rapidly with increasing frequency. We arranged the observation schedules so that the lowest frequency radiometers measured the spectrum during the times of minimum galactic emissions. The three lowest frequencies also measured the galactic emission by scanning in right ascension.

The cold-load calibrator was a large open-mouth dewar containing a very good microwave target. Measurements indicate that the calibrator was a blackbody with an emissivity greater than 0.999. The cold-load calibrator was operated first with LN as the cryogen, then with LHe to make our best measurements. At the three lowest frequencies we expected the temperature difference between the cold-load calibrator (approximately 3.8 K) and the sky (2.8 K cosmic background radiation plus 1 K atmosphere) to be small. As we operated the 3 cm radiometer we could see that the temperature difference was less than 0.1 K--generally on the order of 0.05 K. At the higher frequencies the atmospheric emission was higher, about 4.5 and 12 K at 0.9 and 0.33 cm respectively. These values were about what we expected from our atmospheric model and were in good agreement with previous measurements by ourselves and others. We expect to have preliminary results out by the end of the year.

We plan to return to White Mountain next summer (1983) to repeat the measurements with improved systems and a new radiometer. The new radiometer will be tunable from 1.7 cm to 15 cm to provide contiguous measurements of the spectrum at many wavelengths. A single tunable radiometer has a number of potentially important advantages over several fixed-frequency radiometers. Although the absolute accuracy will be comparable to the fixed-frequency radiometers, the relative accuracy of one measurement to the next should be improved. This is a great benefit in looking for spectral deviations. Traditionally systematic errors have limited the accuracy measurements. Use of a single receiver with one measurement procedure, rather than multiple receivers will help reduce this problem. A tunable system is more likely to find narrow features than fixed-frequency systems and can also detect and avoid isolated points of RF interference more readily.

On the other hand, good broad-bandwidth components are more difficult to design and manufacture than those designed for a single fixed frequency. A particularly important example is the antennas. Fixed-frequency, narrow-bandwidth antennas can be made with very low sidelobes and good impedance matching (low reflection). Thus we cannot use the tunable radiometer to determine the atmospheric emission accurately through zenith scans, since it is too sensitive to the earth's emission. Instead, we will make atmospheric zenith scans with the fixed-frequency radiometers. The repeated and improved fixed-frequency measurements serve also as a cross check of the tuned measurements.

The use of anisotropies and possibly the Sunyaev-Zeldovitch effect to look for spectral distortions has entered a new stage. There is now a sufficient number of quality measurements of the first-order anisotropy over enough frequencies to do comparison fitting to a Planckian spectrum versus a Woody-Richards spectrum. Wright pointed out that the data slightly favor the Planckian spectrum. The near future holds the promise of improved data both from existing data not yet analyzed and from upcoming measurements.

ANISOTROPIES

This system has unveiled a new generation of experiments on both the large and small angular scale. The new large-angular-scale data from the Princeton, Berkeley, and MIT group confirm and more accurately measure the first-order anisotropy, and set upper limits on quadrupole and higher-order anisotropies. New Princeton and Ratan 600 measurements have reduced the upper limits on small-angular-scale anistoropy.

What characterizes this new generation is: (1) significantly improved system performance, (2) substantial sky coverage (and its corollary pointing), (3) improved understanding of the galactic foreground signal, and (4) good calibration. Previous experiments typically had sensitivities of 50 mK for one second of integration; this new generation has sensitivities of about 10 mK for a second of integration. Parijskij reported the best sensitivity, 2 mK for a second of integration at 7.6 cm and sensitivities of 7 and 15 mK at 8.2 and 3.9 cm respectively. These improved sensitivities are the result of new technologies being adapted to anisotropy experiments. Currently the maser systems are providing sensitivity at about the 5 mK level for a one second integration while cryogenically-cooled receivers and bolometers are worse by about a factor of two. All of these represent an astounding improvement in system performance, evidenced by the fact that these systems show the first-order anisotropy in real time during the experiment, while five years ago the effort was to discover and detect that anisotropy.

The improved performance coupled with substantial sky coverage is important for two reasons. First, balanced sky coverage uncorrelates the various moments of a spherical harmonic expansion fit to the data. This allows better limits, simplifies understanding of the stated errors, and reduces the chance that one spherical harmonic might feed power to another. Second, it is now possible to generate sky maps where each resolution element has enough sensitivity to see galactic sources if they are present and with sufficient coverage to see the galactic pattern on the sky. These maps are key in improving understanding of the galactic foreground signal and thus ultimately in understanding the data on cosmic background anisotropy. The structure of the map points out to the experimenter the necessity of understanding the galactic signal and provides a vehicle for testing galactic models. Most of the old and new data for understanding the galactic emission does not come from the anisotropy experiment but from radioastronomical and infrared measurements. These data must be synthesized into a galactic model and tested against the sky map for completeness and correctness. As Wilkinson pointed out there is reason to believe that an incorrect galactic emission model probably accounts for his previously claimed low-frequency quadrupole signal. Possibly galactic dust accounts for the large hot region reported by Melchiorri, Fabbri, and collaborators.

Several groups are soon to be in a position to present additional large-scale anisotropy data. Wilkinson's group not only has nearly complete coverage of the northern sky but also has data taken from a balloon flight in Brazil which they have not yet analyzed. Berkeley (Epstein, Lubin, myself) plans to get southern hemisphere data late this fall or early this winter with our 3 mm (90 GHz) system. Weiss at MIT is trying to arrange for another flight to improve his northern sky coverage and to use his new, more sensitive bolometers. Thus, not only is there new data from the 24 GHz Princeton maser, the 90 GHz Berkeley helium-cooled radiometer, and the 250 GHz MIT pumped-helium-cooled bolometer reported here, but also the expectation of additional data soon to come.

Calibration is the fourth significant improvement that I listed. Calibration is important in two ways: one, the expected and the other, more subtle. With improved sensitivity the first-order anisotropy is measured with smaller statistical errors. In order to compare the results of different measurements, either to look for spectral deviations or to determine the velocity of the galaxy, one needs good calibration. With the improved sensitivity and the attendant desire and need for improved sky coverage, experiments are having to combine data taken from two balloon flights occurring six months or more apart. Flights roughly six months apart are necessary to cover the part of the sky obscured by the sun in the first flight, since the quality data can only be taken at night. If the calibration changes from one flight to the next it introduces a spurious quadrupole signal into the data. Our 3-mm-wavelength anisotropy experiment has a small pop-up calibrator to check the spurious relative gain during the flight and from flight to flight. We are now converting this small pop-up calibrator to a full-beam calibrator in the expectation that it will provide an absolute inflight calibration.

The small scale anisotropy measurements reported by Wilkinson and Parijskij are spectacular in the scale of the apparatus used and the technology of the receivers. They are equally impressive in the scope of their procedures and data analysis. Wilkinson reported a 95% confidence level upper limit of $\Delta T/T$ of 1.1×10^{-4} at a frequency of 19.5 GHz and a beamwidth of 1.5 arcminutes. Parijskij reported a large number of upper limits at different angular scales and frequencies. His most stringent limits were 10^{-5} and 5×10^{-5} for 5 arcminutes and one degree at 7.6 cm wavelength. These very low limits generated spirited discussion about the data processing and source confusion, particularly about how the sources are subtracted. Whatever one's view on the subject, it is now clear that the small-scale anisotropy experiments are also in the business of understanding the foreground galactic emission in order to interpret the anisotropy data properly.

The results of new experiments at both the large- and small-angular scales are very impressive and are a substantial improvement over past measurements. The field of anisotropy measurements has matured greatly as is evident in the sophistication of techniques and understanding of experimental pitfalls.

SUMMARY OF PROPERTIES OF COSMIC BACKGROUND RADIATION

The spectrum is presently well-fitted by a 2.7 K Planckian spectrum in the Rayleigh-Jeans region, although Woody and Richards report a 15% distortion of the best-fitted Planckian spectrum at and above the peak.

The first-order (dipole) anisotropy is now confirmed and well-measured by several groups to be at the 10^{-3} level. The reports of quadrupole anisotropy at the 0.5 to 1 mK level are disputed. There is no evidence for any anisotropies except the diple at greater than the 10^{-4} level.

The upper limit for fractional linear polarization is less than 10^{-4} or 0.3 mK at the 95% confidence level. At Berkeley we have set an upper limit of 10^{-3} on the variation of circular polarization from position to position on the sky. (We have not reported these results yet because there is no easy way to separate a circular polarization signal internal to the apparatus from one in the cosmic background radiation. Thus we can only do difference measurements from position to position and can only fully trust those along fixed declinations for which the polarimeter is not moved or changed.)

The only measurement of the time dependence of the cosmic background radiation that anyone has is a measurement of the photon statistics. If the cosmic background radiation has a thermal origin, then the photons should have a Planckian or at least Bose-Einstein distribution, with the corresponding statistics. Several different groups have begun experiments to check this hypothesis. Bruce Allen, a student working with R. Weiss at MIT, was the first to set up such an experiment. As a result other groups have become interested. De Barnadis, Dall Oglio, et al. reported here the first preliminary results, indicating that in the infrared (near the peak and shorter wavelengths) the background radiation appeared to have the proper (i.e. thermal) photon statistics.

In my opinion one must be prepared for the possibility that at the limits set by astrophysical foregrounds, the cosmic background radiation is described as having a Planckian distribution and is isotropic except for a Doppler-shift induced dipole anisotropy. This possibility provides a very simple description of a very fundamental attribute of the universe.