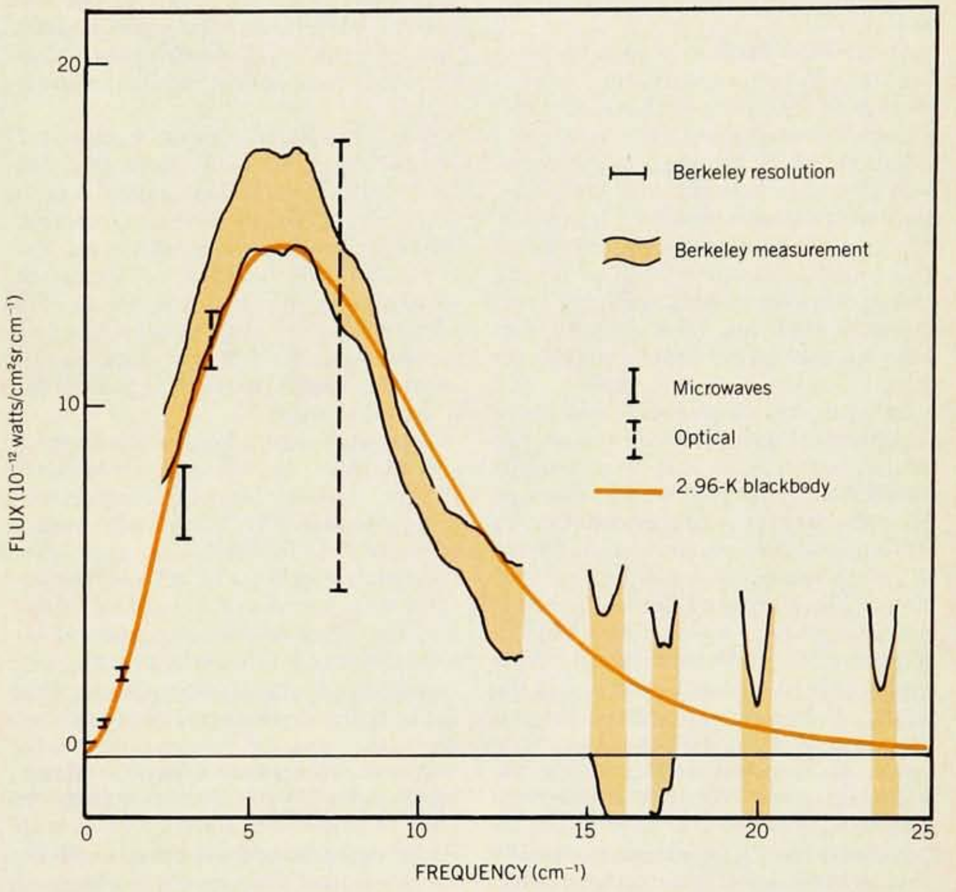
Cosmic background matches blackbody with deviations

Although last year's Nobel prize in physics honored the discovery of the cosmic background radiation in 1965, since then, because the observations are so difficult to make (especially at high frequency), it has only been possible to show that the spectrum is approximately that of a 3-K blackbody. Nevertheless, the evidence for a blackbody spectrum has been sufficiently compelling to convince most cosmologists that the Universe began with a big bang.

Now David P. Woody and Paul L. Richards of the University of California at Berkeley report a measurement[1] of the spectrum of the cosmic background radiation with a balloon-borne spectrophotometer that follows the general shape of a Planck distribution over the broad frequency range from 2.54 to 24 cm^{-1} (or 3.9 mm to 0.42 mm) but shows significant deviations. The long-standing question of whether the spectrum falls at frequencies above the peak has been effectively laid to rest, Richards told us, but tantalizing evidence for deviations from the Planck curve have appeared. The deviation ranges smoothly from about 10% above a 2.96-K Planck spectrum near its peak at 6 cm^{-1} to 20% below it at 11 cm^{-1} (see figure). The measured spectrum differs from the Planck curve by five standard deviations. From previous experiments, the Berkeley group says, it was difficult to detect deviations from the Planck curve as large as 20%.



Spectrum of cosmic background radiation. The solid curve is the spectrum of a 2.96-K blackbody. The orange area is the rms sum of all Berkeley experimental errors with $\pm 1\sigma$ error limits. The gaps are left at 14, 16, 18 and 23 cm^{-1} because of strong atmospheric absorption there.

The Berkeley balloon flight took place two years ago in May. Although the deviations showed up early in the data analysis, Woody and Richards were eager to eliminate all potential sources of error before publishing their results. They had the additional incentive to be certain because a couple of other observations in the past had shown much larger deviations from the blackbody spectrum and had later been shown to be in error.

The new Berkeley experiment uses a vastly improved version of the apparatus used in an earlier Berkeley measurement of the cosmic background, whose results were reported four years ago (PHYSICS TODAY, July 1975, page 17) by Woody (now at Caltech), John Mather (now at Goddard Space Flight Center), Norman Nishioka (UCLA Medical School) and Richards. Both experiments used a Fourier transform infrared spectrometer, immersed in liquid helium, to make absolute flux measurements.

Among the important improvements in the apparatus was an extremely sensitive composite germanium bolometer,[2] cooled to 0.3 K by liquid He^3. The bolometer is a tiny gallium-doped germanium thermometer, attached by epoxy to a thin sapphire sheet. This sapphire is blackened with a bismuth film to absorb radiation and convert it to heat. Using this bolometer improves the detector sensitivity by a factor of forty over the previous Berkeley detector, making it so sensitive that detector noise is no longer a serious limitation, Richards told us.

In the new experiment, to make sure the antenna was looking at the sky, the Berkeley pair used a metal flux concentrator of the type developed by Roland Winston (University of Chicago); the antenna's field of view was 7 deg. To shield the antenna from ground radiation, the team used a 10-m^2 aluminum sheet wrapped around the spectrophotometer. To reduce atmospheric interference, they used a larger balloon than before, so that it could go to 43 km instead of 30 km. Because atmospheric pressure drops exponentially, going to a higher altitude reduced atmospheric effects by a factor of three.

In early measurements of cosmic background, the measurements in the radio range (400 MHz–90 GHz) were the most precise. Typical errors were in the 10–30% range, Richards said. Cosmological limits to spectral measurements come from galactic synchrotron radiation at low frequencies and from cosmic dust at high frequencies. At low frequencies,

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experiments can be done with relatively conventional room-temperature microwave apparatus, he said, but at high frequencies, a helium-cooled infrared device is needed.

At wavelengths near the peak, one can measure the cosmic background radiation by inference from the energy-level populations of interstellar molecules, which can be observed in optical absorption lines in the spectra of certain stars. At frequencies below the peak, measurements can have errors of about 10%. Beyond the peak, however, Richards said, these measurements are much less accurate.

At balloon altitudes, for high frequencies the atmospheric emission has been rising as the third or fourth power of frequency, overwhelming the background radiation, which has been falling exponentially. So there is a high-frequency limit to the measurements. But below this limit, Richards notes, improvements in infrared techniques made by several groups have permitted infrared measurements that are more accurate than most of the earlier low-frequency results.

In the figure, the rms sum of all of the experimental errors is shown as the shaded region with plus or minus one standard deviation error limits. Gaps are left in the data at the frequencies of strong atmospheric lines (roughly 14, 16, 18 and 23 cm^{-1}), where the errors become very large. The integrated flux of the radiation is equivalent to that from a blackbody at 2.96 (+0.04 and −0.06). This spectrum is plotted as a solid line in the figure. For an accurate test of the statistical significance of a fit to a blackbody curve, a distinction was made in the published paper between errors from sources such as detector noise or the atmospheric model, which are essentially uncorrelated across the spectral range, and errors from sources such as the instrumental gain, which move the overall curve up or down. The results of this analysis gave a statistical significance of five standard deviations.

The shape of the spectrum and measurements at different altitudes put strong constraints on possible local sources of the deviation, Woody and Richards say. The same shape occurs in all of the scans (covering about 1.7 steradian of the sky); so the possibility of a few bright sources appears dim. The shape does not fit a power-law spectrum, and its magnitude is much larger that the continuum emission expected from the apparatus, Earth or galactic dust clouds. By measuring at different zenith angles, the experimenters place an 85% confidence level limit on the deviation not being caused by the atmosphere. No significant structure of the type expected for molecular emission shows in the deviation at resolutions down to 0.13 cm^{-1}.

What is the explanation of the results? Richards feels there is no doubt that the cosmic background follows an approximate blackbody curve and is consistent with a big-bang origin for the universe. But it is possible that something has happened to distort its shape. Many papers have discussed the source of possible distortions. However, the Berkeley results do not correspond to any of the likely theories, Richards told us. For example, one theory proposes that photons are scattered by hot electrons, thus heating the photons. This mechanism would cause the spectrum to fall less slowly. Berkeley sees the opposite result. Nevertheless, as Richards notes, "Cosmologists have almost infinite imagination."

Could the Berkeley result be in error? At one level, Richards feels that the Berkeley group has done a good experiment. But at another level, he feels that because the answer is so important, the Berkeley result should be verified before starting to modify one's world view. He worries about the risk of undetected systematic errors and is now changing the observing method as much as possible for a second attempt.

Instead of using a Fourier transform ir spectrometer, he will use narrow-band filters. Instead of subtracting atmospheric emission by fitting it with a computer model, Richards and some new collaborators at Berkeley will scan the sky from close to the zenith to close to the horizon. Because the instrument will be looking through different slant paths, one can evaluate atmospheric effects. He hopes to fly the new apparatus in about one year.

Cosmic Background Explorer. Meanwhile, John Mather, who as a graduate student of Richards started looking with Richards for deviations from a blackbody spectrum nine years ago, is in charge of plans for the Cosmic Background Explorer.[3] Members of the COBE satellite science steering group are Mather and Michael Hauser of Goddard Space Flight Center, Samuel Gulkis of the Jet Propulsion Lab, George Smoot of Berkeley, Rainer Weiss of MIT and David Wilkinson of Princeton. The mission could be launched in 1984 or 1985 if approved by NASA headquarters. The Explorer series has already been approved by Congress.

COBE would carry three experiments: The first would also be an infrared Fourier transform spectrophotometer, but it would go down as far as 0.1 mm and, to calibrate the spectrophotometer, would compare the cosmic background spectrum directly to that of a blackbody source on the satellite.

A second experiment, using differential microwave radiometers, would improve the measurement of anisotropy done by Smoot, Richard Muller and Marc Gorenstein, using a U-2 airplane, and by Wilkinson, using a balloon (PHYSICS TODAY, January 1978, page 17). Because the satellite would hover over the Earth's twilight zone, the entire sky would be scanned over a year's time. The antenna would have a 7-deg beam width, the same as the first COBE experiment and the U-2 experiment, but would be far more sensitive because of the long observing time and the full sky coverage.

The third experiment would look for diffuse infrared background radiation from 2 to 300 microns, a region where only local and galactic sources are known.

—GBL

References

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Magnetic refrigerator–heat pump

For almost half a century low-temperature physicists have been exploiting the adiabatic demagnetization of paramagnetic materials to achieve temperatures near absolute zero. Until recently the potential utility of the magnetic cycle for refrigeration and heat pumping near room temperature has not been taken seriously for two reasons: First of all, the degree of magnetic order achievable in paramagnetic materials at practical field strength becomes very small at room temperature. Thus the entropy change that pumps heat when magnetic fields are applied and withdrawn becomes too small to be useful. Furthermore, by 20 K the lattice entropy changes of typical paramagnetic salts and the magnetic entropy changes from which they must be subtracted in a Carnot refrigeration cycle are comparable.

To circumvent these obstacles in the path of a practical room-temperature magnetic refrigerator–heat pump, Gerald V. Brown and his colleagues at NASA's Lewis Research Center in Cleveland have chosen gadolinium, a ferromagnetic rare earth with a Curie temperature of 293 K, as their magnetic refrigerant. Brown's group has recently reported the successful demonstration of a gadolinium magnetic refrigerator–heat pump,[1] operating near room temperature and producing a temperature difference of 80 kelvins between source and sink. Though the heat-pumping power of this laboratory prototype is still quite modest (maximum 34 watts), Brown considers that the temperature range already achieved makes this device interesting for indoor climate-control applications. A refrigerator