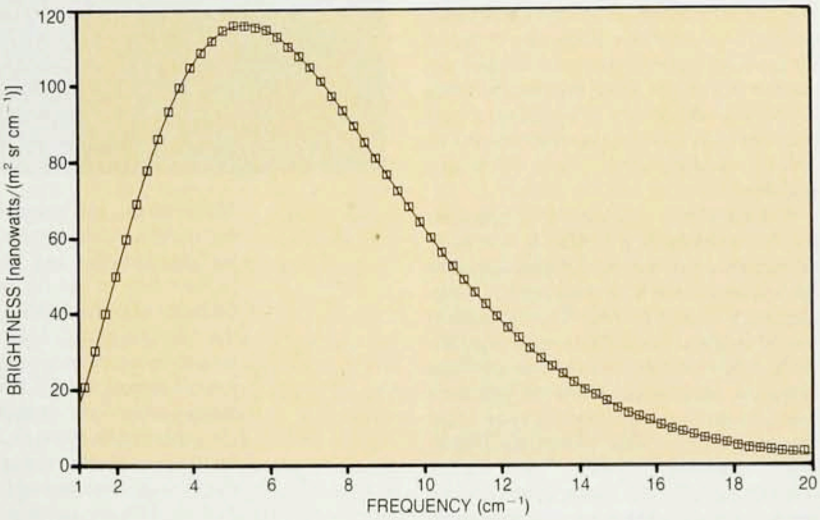
# COBE SATELLITE FINDS NO HINT OF EXCESS IN THE COSMIC MICROWAVE SPECTRUM

For several years cosmologists have been kept busy puzzling over reports of a large excess in the cosmic microwave background spectrum at wavelengths shorter than 1 mm. Now they've been given a brief respite. At the January meeting of the American Astronomical Society in Washington, DC, John Mather of NASA's Goddard Space Flight Center presented the first spectral results[1] from COBE—the Cosmic Background Explorer—which had been launched into Earth orbit just eight weeks earlier. The moment Mather placed the COBE spectrum (reproduced on this page) on the overhead projector, the packed lecture hall burst into sustained applause. The contrast with all the earlier, fragmentary data was astonishing. The spectral measurements, from 1 cm down to 0.5 mm, fit perfectly to a Planck blackbody radiation curve for a temperature of $2.735 \pm 0.06$ K. At the 1% level one could see no deviation from an ideal blackbody spectrum. And it's not just a question of fitting a shape. With only one free parameter—temperature—the normalization also has to come out right. For a given temperature the absolute brightness of a blackbody spectrum is specified.




**Cosmic microwave background spectrum** measured by the Far Infrared Absolute Spectrometer[1] aboard the Cosmic Backgound Explorer. The COBE satellite was launched in November, and these data come from just 9 minutes of early observing near the Galactic north pole. The data points are shown here fitted to a Planck blackbody curve. This fit yields a temperature of $2.735 \pm 0.06$ K. At the level of 1% of peak brightness, these new observations show no deviation from a perfect blackbody spectrum.

These spectacular results come from just 9 minutes of observation near the north Galactic pole by the Far Infrared Absolute Spectrometer. FIRAS is one of the three observing instruments aboard COBE. The north pole of our Galaxy is relatively free of local microwave sources and these were 9 minutes of particularly good thermal stability for FIRAS, making it easy to analyze the data quickly. FIRAS will take data all over the sky for about a year, until COBE's liquid helium cryogen runs out. In the end it should be possible to detect departures from a blackbody spectrum as small as 0.1 % of the peak brightness.

The audience also heard reports of first results from the Differential Microwave Radiometers and the Diffuse Infrared Background Experiment, the other two instrument systems aboard COBE. But the DMR and DIRBE results were at even more preliminary stages than the FIRAS data. George Smoot (Lawrence Berkeley Laboratory) presented the preliminary sky maps shown on page 18, displaying the DMR's first measurements of the variation of radiation intensity from place to place at three microwave wavelengths. Thus far, Smoot told his audience, the sky maps give evidence of no large-scale background variation other than the dipole moment attributed to the "peculiar" motion of our Galaxy toward the Virgo cluster. The DMR has a relatively wide angular resolution of 7°, designed for all-sky surveys and measurements of large-angular-scale cosmological variations. Apart from the well-known dipole variation, the early DMR measurements find that the microwave background is uniform across the sky to a part in $10^4$.

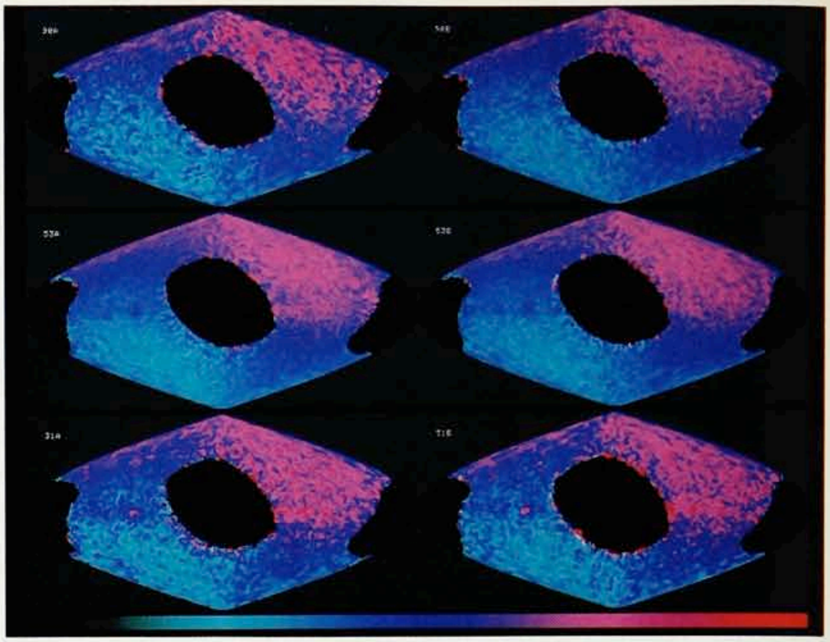
## The blackbody spectrum

Measuring the cosmic microwave spectrum is difficult. At wavelengths shorter than 1 cm, ground-based observers have to contend with molecular-absorption bands in the atmosphere. Rocket and balloon-borne observations are all too brief. COBE is the first orbiting observatory designed for this part of the spectrum. It cannot observe at wavelengths longer than 1 cm, simply because its apertures are too small. Ground-based observations at longer wavelengths suffer only about 1% atmospheric attenuation, but the reradiation of that little bit of absorbed energy adds a spurious 3 K to the apparent temperature of the sky.

The most recent reports of a considerable short-wavelength excess in the cosmic microwave background spectrum had come from measurements with a rocket-borne instrument developed by a collaboration between Nagoya University and the University of California, Berkeley. It was lofted by a sounding rocket to an altitude of 300 km from a Japanese launch site in February 1987 (see PHYSICS TODAY, August 1988, page 17). Experiments of this kind are plagued with systematic uncertainties that are extremely difficult to sort out with the limited diagnostic capabilities of sounding-rocket packages. Paul Richards, leader of the Berkeley contingent, had warned that "given the history of the field, confirmation is certainly required."

Nonetheless, the theorists plunged in. In the standard Big Bang scenario one expects an isotropic cosmic photon background with a blackbody temperature of about 3 K. The radiation would have achieved thermal equilibrium with matter before the profuse creation and absorption of photons came to an end less than a year after the Big Bang. The resulting blackbody spectrum would then have cooled, shifting its peak toward ever longer wavelengths as the universe continued to expand. But if nothing very bizarre happened, the cooling spectrum would have retained its blackbody character through the "recombination time"—some 300 000 years later— and right down to the present day. "Recombination" refers to the neutralization of the cosmic charged plasma (mostly protons and electrons) when the radiation finally cooled down enough to permit the stable existence of neutral atoms. The cosmos was now for the first time transparent. One assumes that most of the microwave photons recorded by COBE have been traveling undisturbed ever since recombination.

The cosmic radiation temperature at recombination would have been 4000 K, corresponding to about 2% of the binding energy of the hydrogen atom. Because the universe has expanded more than a thousandfold in the 10 or 20 billion years since recombination, the blackbody temperature of the cosmic background radiation should by now have redshifted down to the 3 K microwave regime.



**Maps of the microwave sky** from COBE's six Differential Microwave Radiometers, at three frequencies: 90 GHz (top), 53 GHz (middle) and 31.5 GHz (bottom). Colors indicate temperature of the microwave radiation; red is hottest. In these Galactic coordinates the center of our Galaxy is in the middle and the Galactic plane is horizontal. Because of the Sun's position during these three weeks, there were no data from the Galactic center or anticenter. The only large-scale variation to be seen is the dipole anisotropy attributed to our "peculiar" motion, which makes the upper right about 0.2% hotter than the lower left. Otherwise, apart from obvious foreground sources, these preliminary data show the cosmic microwave background to be isotropic to within a part in $10^4$. The red points bordering the central hole are statistical noise where observing had just begun.

## Scenarios

In their attempts to explain blackbody-spectrum distortions of the kind reported by the Nagoya–Berkeley group, with excess radiation at short wavelengths, the theorists have concentrated on hypothetical scenarios taking place long after the recombination time. It is conceivable, for example, that very early superstars or hyperactive protogalaxies released extraordinary amounts of radiant energy that was then reradiated in the infrared by a prodigious density of cosmic dust. But such models had great difficulty coming up with enough energy and dust to fit the Nagoya–Berkeley spectral excess.

Somewhat more plausible were the models that hypothesized the existence of a hot intergalactic medium with a present temperature of 400 million kelvin—suggestively similar to the apparent temperature of the diffuse x-ray background we see around us. This highly ionized medium would have been even hotter (about $10^9$ K) when it was formed, supposedly by a large output of energy from early quasars.

The hot electrons of this imagined intergalactic medium would kick the cosmic background photons up to higher energies by Compton scattering. The dimensionless "Comptonization parameter" $y$ describing the resultant distortion of the blackbody spectrum is essentially an integral of the product of the density and temperature of free electrons over the path of a photon through this medium. A non-negligible $y$ requires that both the density and temperature of free electrons in the intergalactic medium be very high. Mather reported that the absence of any observed short-wavelength excess in the early FIRAS data has already provided an upper limit of 0.001 for $y$. This is small enough to rule out the idea that a hot intergalactic medium is responsible for the diffuse x-ray background. At the same session of the AAS meeting, David Helfand and his Columbia colleagues presented x-ray and radiotelescope data suggesting that high-energy radiation from a large population of faint radio galaxies is sufficient to explain the x-ray background.

As more FIRAS data are compiled and the instrument's calibration is better understood, tiny deviations on the short-wavelength side of the blackbody spectrum may eventually be seen at the level of a few tenths of a percent. "Such deviations would be a real clue as to what went on in the information desert between recombination and the first quasars we can see," says COBE theorist Edward Wright (UCLA). At the spring meeting of The American Physical Society in Washington next month, the FIRAS group will report new spectral data all the way down to 0.1 mm.

### Longer-wavelength distortions

Departures from the blackbody curve at wavelengths longer than a few millimeters would tell us about an earlier era—the time from recombination back to about a year after the Big Bang. In that era the density of ionized matter was sufficient to keep photons from going very far without scattering, but insufficient to permit much creation or absorption of photons. If during that era there was some significant reheating of the electrons in the expanding universe, they would have shared this new thermal energy with the photons. But in the absence of adequate photon-creating mechanisms, the reestablished thermal equilibrium distribution of photons would no longer be an ideal blackbody spectrum. One would see, down to the present day, a Bose–Einstein distribution with a nonvanishing "chemical potential" $\mu$. That is to say, the exponential $\exp(h\nu/kT)$ in the Planck blackbody formula would be replaced by $\exp(h\nu/kT + \mu)$.

The peculiar heat source leading to such a chemical potential might have been the dissipation of extensive plasma turbulence or the decay of some exotic particle species we don't yet know about. In any case, the early FIRAS data show nothing of the kind. The agreement of the long-wavelength data with the Planck formula already sets an upper limit of 0.009 on $\mu$. However, the best place to look for a nonvanishing $\mu$ is at wavelengths longer than 1 cm, where $h\nu/kT$ becomes very small. But that's where COBE runs out of room. Ground-based data have for the last ten years been suggesting a cosmic blackbody temperature slightly lower than 2.7 K. This might be a spurious consequence of atmospheric absorption inadequately considered. On the other hand, it might be a real indication of a positive chemical potential. "If FIRAS can pin down the spectral brightness at half a centimeter to within 0.1%," Wright told us, "we'll be able to put a really meaningful limit on $\mu$."

FIRAS is a Michelson interferometer spectrometer that employs two blackbodies with adjustable temperatures: an internal reference source and an external calibrator. The calibrator, which comes within 0.01% of being a perfect blackbody, can be moved to cover the entrance of the instrument's input horn, much like a trumpet mute. The absolute brightness spectrum of the cosmic microwave background is determined with great accuracy by adjusting the temperature of the internal reference source to null out the input from the sky as nearly as possible and then interposing the calibrator in place of the sky.

Meanwhile the ground-based observers have not been idle. A Berkeley–Milan collaboration that operates a new microwave spectrometer at the South Pole will report its first results for wavelengths longer than 1 cm at the April APS meeting. This collaboration includes Smoot and other members of COBE's Lawrence Berkeley Lab contingent wearing two hats.

### Differential radiometers

The preliminary sky maps shown on page 18 were obtained from three weeks of DMR observing at 31, 53 and 90 GHz, corresponding to wavelengths of 9.5, 5.7 and 3.3 mm, respectively. The maps are shown in Galactic coordinates. The empty space in the middle of each map covers the center of our Galaxy, in which direction DMR had not yet taken data. The plane of the Galaxy is horizontal. Because COBE's principal concerns are cosmological, microwave signals from the Galaxy or other nearby sources represent unwanted foreground obfuscation. The DMR is in fact six separate radiometers, two for each receiving frequency. These frequencies were carefully chosen to optimize the distinction between local sources and the cosmic background.

The upper right-hand region of each map is about 0.1% hotter than the mean, and the lower left-hand region is correspondingly cooler. This is simply the well-known dipole asymmetry attributed to the Doppler shifting of the microwave background by our own motion relative to the privileged "comoving reference frame" in which the cosmic background is presumed to be isotropic. Other hot spots and mottling appearing on these maps are attributed to foreground sources or statistical noise. True cosmological hot spots would show up at all three frequencies. Even though the statistics are still very limited, and parts of the sky have not yet been covered, these maps represent the most extensive all-sky microwave survey yet available. At this early stage, the DMR data indicated no effective temperature variation $\Delta T$ from place to place in the cosmic microwave background (except for the Doppler dipole moment) at the level of $10^{-4}$ in $\Delta T/T$.

Radiotelescope measurements with much finer angular resolution—on the order of minutes of arc rather than degrees—have already confirmed[2] the uniformity of the microwave background in some directions to a few parts in $10^5$. But such fine-grained measurements are of necessity limited to small patches of sky. The search for fluctuations on the arcminute scale is particularly relevant to the difficult question of how the universe managed to evolve from the seemingly wrinkle-free time of recombination to the present richly patterned epoch of gaping voids and superclusters of galaxies more than 100 million light years across. Even the largest of these structures—the 170-megaparsec "Great Wall" of galaxies recently reported by Margaret Geller and John Huchra[3] of the Harvard–Smithsonian Center for Astrophysics—would have grown from a seed fluctuation extending over less than one degree of arc in the microwave background.

### Cosmic multipoles

With its 7° angular resolution, the DMR is primarily searching for much larger-scale variations across the sky, which one would parametrize in terms of the quadrupole, octopole, hexadecapole and higher moments of the angular distribution of cosmic microwave temperatures. (Any intrinsic cosmological dipole moment would be masked by the Doppler effect of our peculiar motion.) The inflationary Big Bang model does in fact call for such large-scale anisotropies, originating from the large-scale end of the model's initial spectrum of fluctuations. Indeed it predicts definite ratios for the quadrupole, octopole and hexadecapole moments.

Though these predicted variations are large in angular scale, they are very small in amplitude. The $10^{-4}$ uniformity of the early data is not yet in conflict with the inflationary model. The DMR is expected to continue taking data for another year after the liquid helium runs out, because unlike the other COBE instruments, it does not require cryogenics. In the end, the DMR will have mapped the entire sky several times over with the $10^{-5}$ sensitivity necessary to address these predictions. The DMR achieves its high sensitivity to small temperature differences between patches of sky by continually switching a single receiver between two identical horn antennae pointing in different directions. The radiometers sweep the sky as the spacecraft spins on its axis and its near-polar orbit stays close to the Earth's twilight zone.

If it turns out that the cosmological quadrupole moment is much larger, relative to the higher moments, than is required by the standard inflationary model, one will have to think of more exotic explanations: Perhaps the universe as a whole is spinning, or the general expansion is not isotropic. "There are perfectly good models for a nonisotropic Big Bang," Wright told us. "The only way to discard them is with the COBE data." At the Washington AAS meeting Smoot pointed out that the early DMR data already put an upper limit on the cosmic quadrupole moment that translates into a reassuring limit on how fast the universe might be spinning. "If it is spinning," he said, " it seems to have completed less than a thousandth of a turn since the Big Bang."

—BERTRAM SCHWARZSCHILD

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# DO OXIDE SUPERCONDUCTORS BEHAVE AS FERMI LIQUIDS?

When a photon knocks an electron out of a material, the freed electron reveals some secrets about the electronic environment it left behind. Such clues are sought by theorists puzzling over the mechanisms for high-temperature superconductivity, but high-resolution data have only become available in the past year. The behavior they reveal resembles the familiar patterns of conventional superconductors in the normal states—but with subtle and complex deviations that are now the focus of intense theoretical attention. The data have confirmed earlier measurements of a superconducting gap and provided direct evidence for a Fermi edge in momentum space.

Traditionally, photoemission measurements, which are very useful for studying metals, insulators and semiconductors, have not been applied to conventional superconductors because these methods do not have sufficiently fine energy resolution to probe the energy region of greatest interest in a superconductor—the narrow forbidden-energy gap that opens as electrons near the Fermi surface pair up at slightly lower energy in the superconducting state. According to the BCS theory, which has been so successful in describing conventional superconductors, the size of the superconductivity gap depends on the critical temperature. Thus if the same mechanism is responsible for the superconductivity in the oxide materials, whose critical temperatures are about ten times higher, the superconductivity gap is expected to be within the reach of photoemission experiments.

Furthermore photoemission offers a unique opportunity to probe the behavior of the Fermi surface both above and below the critical temperature. Not only are such experiments of renewed interest, but recent improvements in sample preparation and increases in angular and energy resolution have given these techniques the required sensitivity.

### Normal-state behavior

Angle-resolved photoemission data are uniquely qualified to answer the question of whether the oxide materials behave as Fermi liquids in their normal state. As described by Lev Landau, a Fermi liquid is a system of weakly interacting particles, known as quasiparticles, whose behavior is qualitatively similar to that of a system of noninteracting fermions. The Fermi liquid has formed the conceptual framework for understanding the behavior of the low-temperature superconductors above their critical temperatures. Although there is no *a priori* reason why the oxide superconductors should act as Fermi liquids, many researchers have tended to compare the observed behavior to this standard. It serves for them as a starting point from which they might extend the theory to explain high-temperature superconductivity. Others have nearly completely scrapped this viewpoint and have proposed new mechanisms of interaction that depart radically from the BCS theory. One such approach is the resonating-valence-bond theory, which envisions that the departure of the electron creates not a hole but two entities—a chargeless "spinon" and a spinless, charged "holon."

In Fermi liquids the locus of points in **k** space defines a Fermi surface (**k** is the lattice wavevector for zero-energy single-particle excitations). All electrons in the system must be accommodated within the volume of this surface in momentum space. If quasiparticles exist, they should give rise to a peak in the energy spectrum, with that peak growing more narrow as **k** approaches the Fermi momentum. Beyond the Fermi energy the peak should disappear. By measuring the energy spectrum for different photoelectron emission angles researchers can essentially probe different regions of **k** space and determine whether the quasiparticle peak exists and how it behaves as the Fermi momentum is approached.

In photoemission studies, the incoming photon gives essentially all its energy to a single electron, which is assumed not to have appreciable interactions as it leaves the crystal. The momentum of the photon is negligible, so that the electron that emerges has momentum nearly opposite to that of electrons remaining behind in the sample. The most energetic electrons ejected come from the Fermi surface. To locate the position of the Fermi surface the experimenters first measure the energy spectrum of a normal metal. Then, with the same initial value of photon energy, they measure the energy spectrum at selected emission angles. Three groups have published angle-resolved photoemission spectra, all on the compound $Bi_2Sr_2CaCu_2O_8$, for which it is easy to prepare high-quality, chemically stable single-crystalline surfaces.

The figure on page 21 shows the energy distribution reported by an experiment[1] that has simultaneously both high angular and energy resolution (30 meV). It was performed at the Synchrotron Radiation Center of the University of Wisconsin by a collaboration consisting of Clifford Olson, Rong Liu, An-Ban Yang and David Lynch (Iowa State University), Scott List and Al Arko (Los Alamos National Laboratory) and Boyd Veal, Ying Chuan Chang, Pei-Zhi Jiang and Paul Paulikas (Argonne National Laboratory). Similar results[2] with better angular resolution and somewhat lower energy resolution were obtained by group working at HASYLAB in Hamburg, West Germany. The researchers there are Recardo Manzke, T. Buslaps and R. Claessen (University