Rocket Measurement of the Cosmic-Background-Radiation mm-Wave Spectrum

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We report here the most precise constraint to date on the spectrum of the cosmic background radiation (CBR), obtained from measurements made with a liquid-helium-cooled spectrometer carried above the atmosphere on a rocket. The spectrum is very well fitted by a Planck function of temperature $T=2.736$ K. The scatter of the equivalent temperature in the band 3–16 cm^{-1} is ± 10 mK, about $\frac{1}{3}$% of the mean whereas the estimated overall accuracy of the mean temperature is ± 17 mK. These results are inconsistent with a previously reported excess ir intensity in the CBR but are in good agreement with COBE results.

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The cosmic background radiation (CBR), discovered in 1965,[1] is a very important observable for the field of cosmology, being one of the oldest entities accessible to measurement. In the simple big-bang scenario,[2–4] it is identified as highly redshifted radiation which was in equilibrium with matter just as the temperature of the Universe fell to a value permitting the formation of neutral hydrogen. In this standard model the spectrum of the CBR would be strictly Planckian (or thermal), this form remaining invariant under expansion of the Universe; early measurements were consistent with a temperature of about 2.7 K.[5] For values of the redshift parameter z less than about 10^7, however, radiation-matter interactions are insufficient to completely thermalize the radiation spectrum in case it is perturbed. Thus, energy-releasing processes occurring since that time can be expected to have left their imprint on the CBR, and accurate measurements of deviations from a Planckian spectrum can give important information about such processes.[6] In the range $10^7 \gtrsim z \gtrsim 10^4$ conditions would be such that kinetic equilibrium, but not thermodynamic equilibrium, is established between electrons and photons, resulting in a Bose-Einstein spectrum characterized by a chemical potential μ, a measure of the deposition of energy relative to the radiative energy density. For $z \lesssim 10^4$, even kinetic equilibrium cannot be established, but Compton scattering occurs resulting in a typical spectrum characterized by a "Comptonization" parameter y, a measure of the discrepancy between electron and radiative temperatures. The results reported here set close constraints on both μ and y.

There are several difficulties in making detailed checks on the thermal nature of the spectrum over a wide spectral range. First, since the Earth's atmosphere is opaque at wavelengths where the CBR is expected to be most intense ($\lambda \lesssim 2$ mm), measurements in this important spectral range need to be made from high altitude. Second, the low temperature of the source necessitates the use of cryogenic techniques to minimize contaminating radiation of the measuring instrument itself. And third, since the radiation is of such low intensity, one needs to avoid sources such as the Earth, the Sun, or dust in the plane of our galaxy.

Based on experience gained with earlier attempts to measure the CBR spectrum from rockets,[7–9] a new instrument, COBRA, was developed and tested during the 1980s.[10] The principle of its operation is illustrated in Fig. 1. By means of a horn telescope, radiation from the sky is directed to one side of a differential polarizing two-beam interferometer of symmetric construction; the second side of the interferometer is illuminated by an

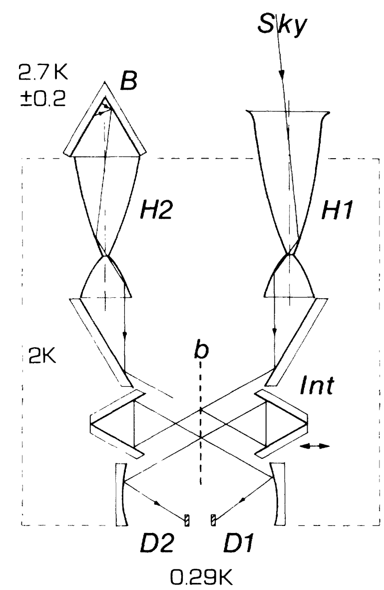

FIG. 1. A diagram showing the principle of the apparatus. $H1$ and $H2$ are similar horn-type telescopes of 6° field of view. $H1$ receives radiation from the sky whereas $H2$ is illuminated by a blackbordy simulator B. Radiation issuing from the horns enters a two-beam interferometer (Int), with a beam splitter at b, from whence it emerges to be focused on two bolometric detectors, $D1$ and $D2$. As the path difference in the interferometer is changed the signal generated by each detector (interferogram) is proportional to the *difference* in intensity of the sky and the blackbody. The numbers indicate temperatures of various sections of the spectrometer.

identical telescope, terminated, however, by a conical blackbody simulator (calibrator) made of Pyrex.[11] As the path difference is varied, each of two detectors on the output side of the interferometer generates an interferogram whose amplitude is proportional to the *difference* in intensity between the sky and the blackbody. If the spectrum of the sky were thermal, and the temperature matched that of the calibrator, null interferograms would be produced; deviations from a null interferogram would show immediately that distortions of the CBR are present. The absolute sensitivity of the device is determined by periodically stepping the calibrator temperature through three values separated by 0.2 K near the expected sky temperature. Power spectra are obtained from a Fourier analysis of the interferograms. Measuring spectra in flight at three different internal radiator temperatures allows calculation of the sky emission spectrum without achieving a null and without reference to ground calibration data.

Extensive measurements were made in the laboratory where the sky telescope aperture was filled by an independent blackbody simulator formed by a large hollow Eccosorb[11] cone whose emissivity is calculated to be more than 0.999 and whose temperature could be set anywhere in the range 1.8–4.2 K independently of the temperature of the instrument. On the basis of null spectra obtained throughout this range by matching the temperatures of the internal and external blackbodies one concludes that the emissivity of the internal blackbody exceeds 0.999, that the two arms of the instrument are balanced to this level, and that interferogram offsets due to stray radiation within the instrument are reproducible and small. At null, the discrepancy between the temperature of the internal calibrator, determined by thermometry, and that of the external blackbody determined from the vapor pressure of the liquid-helium coolant, is less than ± 5 mK; it is believed to arise from nonuniformity of temperature within the internal calibrator. This sets a basic limit to the accuracy of this apparatus. Detector noise in this context is negligible, amounting to about ± 1 mK in 1 min of observing time.

The instrument was launched from the White Sands Missile Range, New Mexico, on 20 January 1990 at 23:05 MST. In launch condition prior to liftoff the sky-telescope port is closed by a vacuum door, the inside being at a temperature of about 20 K. During ascent this door was opened at 150-km altitude allowing the observation of deep space; it was closed at 100 km on descent. The apogee was 250 km. In the observation period, of about 5-min duration, a total of 166 interferograms was recorded for each detector. During this period the telescope, which has a 6° field of view, was pointing in the direction $b = 25°$, $l = 184°$ in galactic coordinates. This region was chosen with reference to far-ir maps of

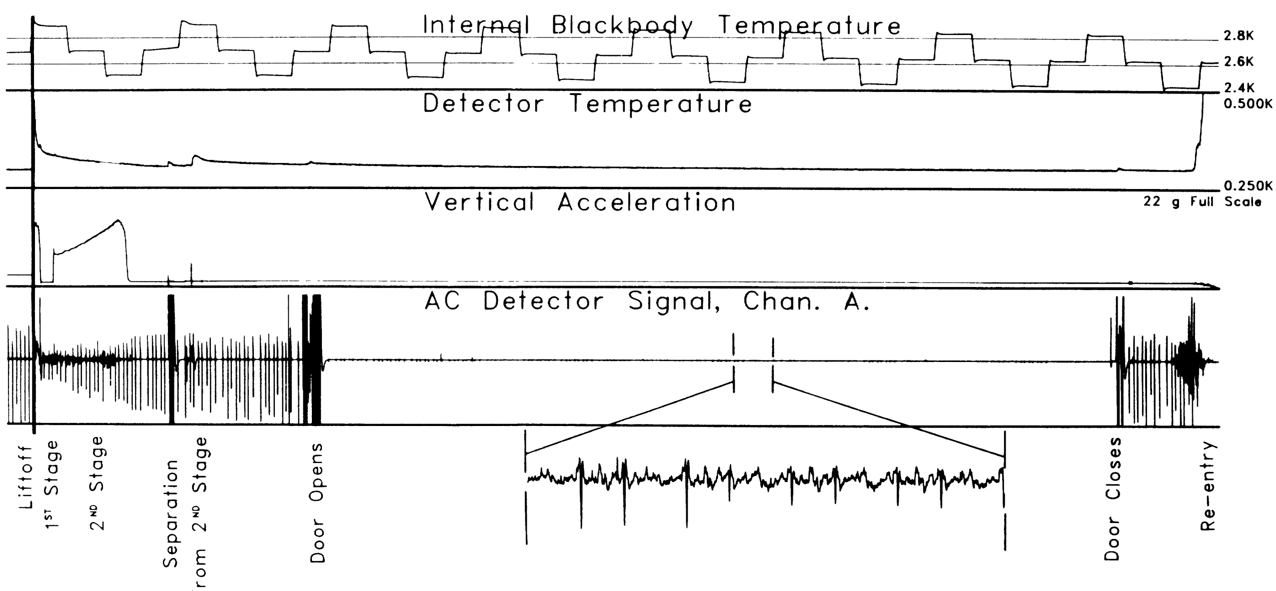

FIG. 2. Signals telemetered to ground during the rocket flight, which lasted 9 min. The top curve shows the temperature of the internal calibrator which cycles through three steps; the average temperature drifted downwards slightly because of cooling of the main liquid-helium bath. The next curve shows the detector temperature which rose at liftoff due to vibration, but which was reestablished at 0.3 K through the sky-observing period. The third curve is the vertical acceleration which reached a peak of 16*g* towards the burnout of the second stage. The last curve is from one of the detectors; for the first 2 min very-large-amplitude interferograms are recorded because the sky telescope sees the back of a vacuum door at about 20 K. As soon as the door opens the signal drops dramatically. Enlarged inset: Interferograms from the sky; the sudden drop in amplitude is due to a 200-mK change in the temperature of the internal calibrator to which the sky is compared. Recall that the peak height of these interferograms is proportional to the difference in radiated power between the sky and the internal calibrator.

diffuse galactic radiation,[12] being free of strong sources. During flight the Sun and Moon were both beneath the Earth's horizon, which itself was always more than 90° from the telescope axis. Laboratory measurements of the telescopes beam pattern limit the response at this angle to be less than 10^{-9}.

A composite graph showing a selection of some relevant data during the flight is shown in Fig. 2. Average interferograms for each of the three conditions of calibrator temperature have been produced for each detector, from which it is possible to make an absolute calibration of the sensitivity, and evaluate the spectrum of sky emission. The average of the two detector results is shown in Fig. 3(a) as an intensity spectrum, and in Fig. 3(b) as an equivalent blackbody temperature as a function of frequency.

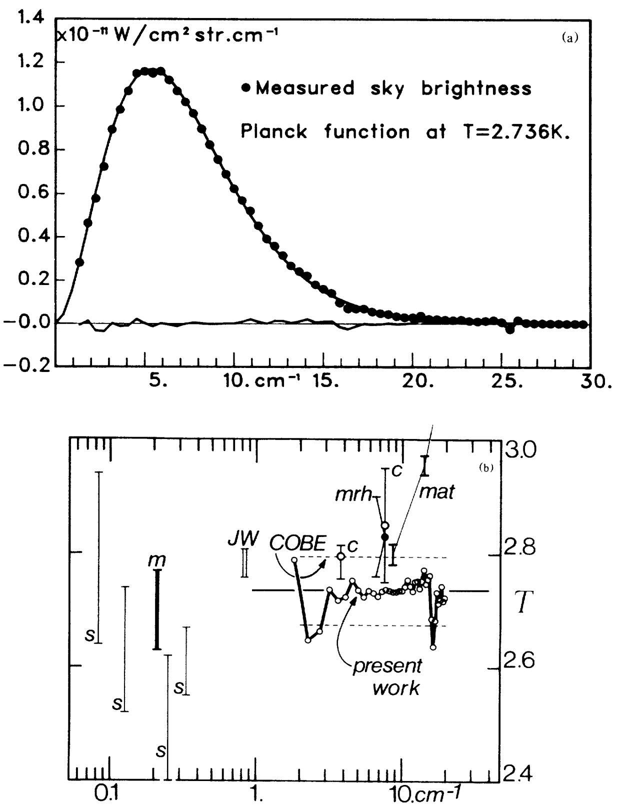

FIG. 3. (a) The intensity of the sky as a function of wave number as measured by COBRA. It is derived from an analysis of all the interferograms recorded while the observation door was open. The smooth curve is a Planck function which fits the data well. The curve oscillating along the abscissa axis is the difference between the experimental and Planck curves. (b) The equivalent blackbody temperature as a function of frequency. Results of COBRA inferred from the data in (a) are shown as circles. The scatter at the band ends was caused by microphonic pickup. Other recent data have been plotted on the same graph: s, Smoot (Ref. 18); JW, Johnson and Wilkinson (Ref. 19); c, Crane *et al.* (Ref. 13); mrh, Meyer, Roth, and Hawkins (Ref. 14); mat, Matsumoto *et al.* (Ref. 16); m, Mandolesi *et al.* (Ref. 20). The dotted lines are upper and lower limits found by FIRAS on COBE (Ref. 17). Note added: Kaiser and Wright (Ref. 15) measure $T=2.74 \pm 0.05$ from CN at $\lambda=2.64$ mm.

In Fig. 3(a), in addition to the measured data, a Planck function has been drawn corresponding to a temperature of 2.736 K, as well as the deviation between the data and the calculated curve. The fit is quite good. The quality of the fit may be judged from Fig. 3(b). In the frequency region $3 \leq \nu \leq 16$ cm^{-1}, where the signal-to-noise ratio is high, the rms scatter of the temperature is 9.5 mK, about $\frac{1}{3}$% of the mean. The standard deviation of the mean temperature equals 2 mK. Outside of this band the confidence of the temperature measurement is not good, in part because the power available to absolutely calibrate the instrument is very small, and in part because the power is insensitive to T. Nevertheless, one can say with considerable certainty that for $20 \leq \nu \leq 30$ cm^{-1} the temperature is less than 3 K, a new upper limit in this region. Further analysis is underway to establish precise confidence levels for this limit.

Various factors contribute to uncertainty in the measured value for the mean temperature: (1) internal calibrator nonuniformity, contributing an estimated 5 mK; (2) uncertainties in offset corrections, 3 mK (the uncorrected offsets are of the order of 30 mK); (3) possible noncancellation of microphonics which developed during liftoff, 2 mK (the microphonic disturbance is common to the two detectors whereas optical signals are exactly out of phase, so microphonics cancel in taking the difference between interferograms measured by the two detectors); (4) statistical fluctuations in the measured spectrum, 2 mK; (5) uncertainties due to heating of the sky telescope by temporary coupling to the warm door during liftoff, 5 mK (this perturbation is shown to be at least this small by comparing interferograms measured at various horn temperatures). The *linear* sum of these uncertainties equals 17 mK. It is expected that further analysis may reduce the magnitude of uncertainties (1), (3), and (5).

The above conservative estimate of the uncertainty of the temperature of the CBR is the smallest of any measurement of this quantity yet reported and provides a reference against which other measurements can be compared in search for spectral distortions. Referring to Fig. 3(b), this measurement falls slightly below previous single-frequency (CN) determinations in the same frequency range,[13-15] and particularly below the broadband rocket measurements[16] which differ from our results by about 4σ, 12σ, and 17σ in their three bands. The latter were interpreted as due to large infrared distortions in the CBR; these distortions are inconsistent with our results. In due course, the systematic errors of the COBE experiment[17] are expected to be understood and the corresponding error bars reduced. At that time it will be fruitful to make a detailed comparison between the results of these two precise experiments. The fact that the mean temperatures agree to within 1 mK, much less than the stated errors, must be regarded as a coincidence at the present time.

The fact that the spectrum is so closely fitted by a Planck function allows one to set a close constraint on both distortion parameters y and μ. Using the stated temperature errors, and only our own data, we find that $y \lesssim 0.001$. This places a limit on the electron energy, and hence constrains postrecombination energy input to ionized matter through processes such as galactic explosions. Similarly, a limit of $\mu \lesssim 0.008$ is implied by these results, assuming μ to be frequency independent. These limits correspond to conservative 95% confidence levels and put constraints on prerecombination energy-releasing processes such as the decay of exotic particles.

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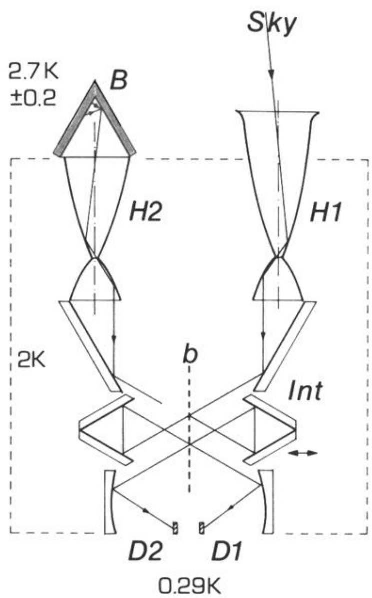

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