Rocket Measurement of the Cosmic Background Submillimeter Spectrum

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Measurements of the spectrum of the night sky have been made in the wave-number region 5 to 35 cm^{-1} with use of a liquid-helium–cooled rocket-borne interferometer. The observed spectrum deviates from a 2.7-K Planck spectrum, there being a deficit of energy between 5 and 11 cm^{-1} and an excess at higher wave numbers.

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The spectrum of the cosmic background radiation (CBR) has a direct bearing on our understanding of the universe, and in particular its thermal history.[1-4] Although many measurements have been made for wavelengths greater than about 3 mm,[5] fewer data are available in the shorter-wavelength region accessible only at high altitude.[6-13] In the present paper the first observation of the submillimeter spectrum of the CBR from a rocket is reported.[14]

The instrument employed, to be described in detail separately,[15] consists of a liquid-helium–cooled, rapid-scan, two-beam interferometer provided with well-shielded optics to view the sky, followed by a bolometer operating near 0.3 K.[16] The optical axis was coincident with the rocket axis to within about 2°. The effective solid angle of acceptance equaled 0.0425 sr, and the field of view between half-power points equaled 13°. The response to a point source 90° off the axis, calculated with use of the geometrical theory of diffraction,[17] equaled 0.16×10^{-6} and 0.43×10^{-8} at 10 and 25 cm^{-1}, respectively, times the on-axis response. The warm top of the instrument was below the rim of the cold horn-shaped entrance aperture of the antenna, and it radiated a negligible amount of power into the instrument. On the other hand, thermal radiation generated within the low-temperature part of the instrument itself made a substantial contribution to every interferogram. Because this contribution is the same for an unknown and a standard source, its effect is eliminated by expressing the unknown source spectrum $S_u(\sigma)$ in terms of the standard source spectrum $S_T(\sigma)$ and the transforms of the interferograms of the unknown and standard sources, $F_u(\sigma)$ and $F_T(\sigma)$, as follows:

$$S_u(\sigma) = S_T(\sigma) + [F_u(\sigma) - F_T(\sigma)]/P(\sigma).$$

The power sensitivity $P(\sigma)$ was obtained in the laboratory from interferograms of a calibrating source. A linear fit was made at a series of calibrator temperatures in the range 4.2 to 1.8 K of the Fourier transform $F_T(\sigma_i)$ of the interferograms, at chosen wave numbers σ_i, to the power emitted by the calibrator at the specified temperature T and wave number. To minimize errors in $S_u(\sigma)$ arising from imperfect knowledge of $P(\sigma)$ one chooses the temperature T near that of the sky, so that $F_u(\sigma) - F_T(\sigma)$ is relatively small. A reference surface within the instrument was available for periodical secondary calibration.

The calibrator was a liquid-helium–cooled conical cavity of half-angle 11°, made of sand-blasted stainless steel, filling the entire aperture of the instrument. Its emissivity, equal to 0.61, was calculated with use of (extrapolated) published values of the same for similar material,[18] and the fact that a ray emitted by the instrument suffers eight reflections before escaping from the cone.

The apparatus has been flown twice, but only the results of the second flight, which took place on 24 Nov. 1978, will be reported here. The launch vehicle was a two-stage NIKE-BLACK BRANT VB rocket,[19] launched from the Churchill Research Range, Churchill, Manitoba.[20] The following events took place: clamshell release at 70-km altitude; payload and rocket despin, 90 km; payload-motor separation, 120 km; observation door opening, 150 km, and closing, 150 km (down leg); and parachute recovery. The instrument functioned properly throughout the flight and was returned to the laboratory in good condition, permitting calibrations to be repeated. Apogee occurred at 370 km. The optical axis of the instrument precessed slowly about the direction $\delta = 51°06'$, R. A. = 2:42:52 h ($l = 140.6°$, $b = -7.6°$), tipped 6° away from it; consequently during part of the flight the galactic plane was in the field of view. At all times the sun and moon were below the horizon, which was 87° or more off the optical axis. The diffraction calculations showed that the contribution to the signal from earth radiation was less than 0.3% that of a 2.9-K isotropic cosmic background at $\sigma = 10$ cm^{-1}.

When the observation door was first opened expected signals were obtained, but shortly thereafter a perturbation at 1-hz frequency suddenly appeared, synchronized with the spin of the payload. It subsequently slowly decayed. Recent information supplied by the rocket manufacturer reveals that it arose from the rocket motor, which slowly overtook the payload because of a residual after-burnout thrust. The signal vanished when the detector viewed the internal reference surface. A ten-second section of the detector signal recorded during the middle part of the flight is shown in Fig. 1(a). It was possible to obtain a corrected interferogram, Fig. 1(c), by subtracting a model of the perturbation, Fig. 1(b). For the last recorded interferogram the perturbation was approximately one-half as strong as shown here. The amplitude of the interferograms was essentially uncorrelated with the phase of the perturbation, and hence the latter arises in large measure from radiation of wave number greater than about 35 cm^{-1} which is not modulated by changes in interferometer path difference.[21]

During flight the interferograms changed in amplitude with time because the instrument slowly cooled, helium gas being exhausted to space. Of these, fourteen, corresponding to 100 sec of observation, were sufficiently free from extraneous radiation and telemetry interference to warrant analysis. Their time dependence was taken into account by fitting to a two-parameter function of the time the intensity at each frequency of the transformed interferograms. The 90% confidence levels of the fitted transform at the last observation time are shown in Fig. 2. To deduce the true spectrum from the fitted transform a post-flight calibration was performed at the instrument's final temperature of 3.3 K. Interferograms from the internal reference source during flight and calibration were very similar. A transformed interferogram of the calibrator, also at a temperature of 3.3 K, is shown in Fig. 2 as a dashed line. Note that this curve bears little resemblance to a Planck curve, because the detector signal arises only from differences in emissivity of the various optical components in the interferometer, and the calibrator. By use of the power sensitivity $P(\sigma)$ of the instrument, also shown in Fig. 2, the spectrum of the sky was then calculated. It is displayed in Fig. 3 with a 2.7-K Planck spectrum for comparison.

The spectrum falls below the 2.7-K curve for wave numbers between about 4 and 11 cm^{-1} whereas it is above this curve for wave numbers between 11 and 35 cm^{-1}. In this latter region the increase with frequency is believed to be largely due to the back of the rocket motor. An estimate of the intensity of its contaminating radiation is shown in Fig. 3 by the dot-dashed line.[22] When this is subtracted from the observed spectrum one obtains the result shown in Fig. 4. The corrected intensity falls with increasing frequency but it does not closely follow a Planck curve. The most conspicuous deviation is a "bump" between about 11 and 20 cm^{-1} where the intensity is in ex-

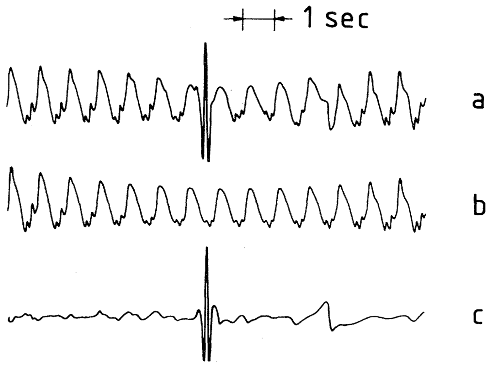

FIG. 1. (a) Section of telemetry record of detector signal, instrument looking at the sky. (b) Model of extraneous signal. (c) Difference between (a) and (b), clearly showing interferogram. The bump midway on the right-hand side resulted from a telemetry dropout.

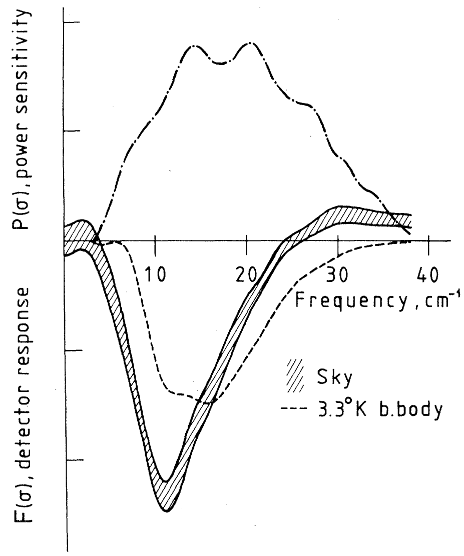

FIG. 2. Dot-dashed line: optical power sensitivity of the instrument. Dashed line: uncorrected spectrum of 3.3-K calibrator. Cross-hatched region: 90% confidence level, uncorrected spectrum of sky, on same scale as calibrator spectrum.

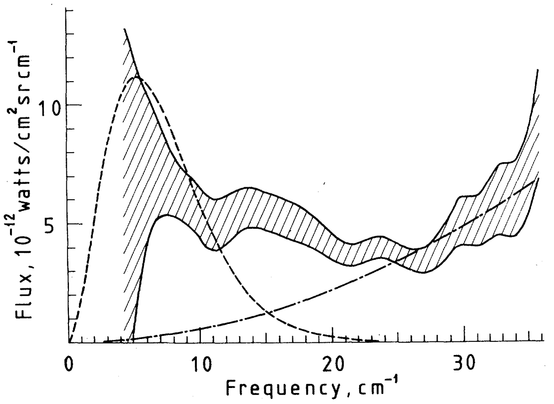

FIG. 3. The flux deduced from Fig. 2. The dot-dashed line is probable contamination form the spent rocket motor. The dashed line is a Planck spectrum corresponding to a temperature of 2.7 K.

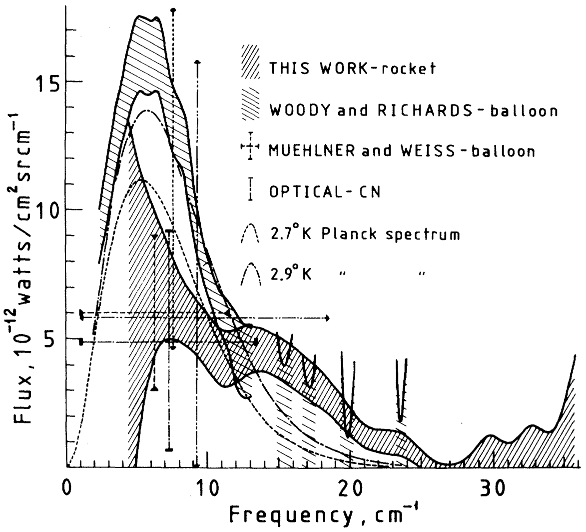

FIG. 4. Flux corrected for spurious radiation compared with measurements of Woody and Richards (Ref. 12), Muehlner and Weiss (Ref. 9), and CN measurements (Ref. 24). In addition, two Planck spectra are shown for temperatures of 2.7 and 2.9 K.

cess of that of either a 2.7- or 2.9-K spectrum. At the present time no convincing explanation for this feature can be offered. Although one might suspect a contribution from the galactic plane, there are no known strong sources at the particular galactic longitudes within the field of view.[23]

In the same figure the recent measurements of Woody and Richards[12] (WR), the broadband-filter measurements of Muehlner and Weiss,[9] and the intensity derived from optical observations of the CN lines by Hegyi, Traub, and Carleton,[24] as corrected by Danese and De Zotti,[5] have been plotted for purposes of comparison. The present measurements are consistent with the broadband ones but they are significantly different from those of WR. The reason for this discrepancy is not clear. The most obvious thing to suspect is the calibration of the rocket instrument. However, the change in $P(\sigma)$ required to make our measurements roughly agree with those of WR is large, and an error of this magnitude, although it cannot be ruled out completely, is unlikely. One might also suspect that removing the spurious periodic signal depressed the low-frequency content of the interferograms. This point was checked by calculations on synthetic signals and found not to be the case. Further rocket experiments with obvious improvements in deployment of the apparatus at altitude are clearly desirable to check the present measurements. On the other hand, the latter show that significant information about the CBR can be obtained from a rocket in spite of the short observing time.

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[19] Bristol Aerospace Ltd., Winnipeg, Canada.

[20] Managed by the Space Research Facilities Branch of the National Research Council, Ottawa, Canada. The payload was instrumented by SED Systems, Saskatoon, Canada.

[21] The modulation efficiency decreases at high optical frequencies because of electrical high-frequency roll-off of the detector amplifier combination. On the other hand, the instrument is sensitive to an externally modulated source out to a wave number of about 60 cm^{-1}, this limit being set by a fused-quartz lens in the optical train. Near-infrared and visible radiation is blocked by a black polyethylene filter.

[22] The position of the rocket motor relative to the payload was calculated from post-burnout acceleration data supplied by the manufacturer. At the end of the data-collecting period the motor subtended a solid angle of 5.8×10^{-7} sr at the instrument and it was 7° off axis. The solid angle of acceptance of the instrument was 0.0425 sr. With the manufacturer's supplied temperature profile across the back of the motor and the assumption of emissivity, the power at the instrument was calculated. Because the motor was within the geometric-optics–accepted beam of the instrument "antenna," no diffraction corrections were applied. Hence the contaminating spectrum is proportional to σ^2. The estimate could be in error because the off-axis angle could be somewhat greater, but not much smaller, than 7°. The amplitude of the perturbing spectrum could thus be smaller than shown, but not larger.

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