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A PRELIMINARY MEASUREMENT OF THE COSMIC MICROWAVE BACKGROUND SPECTRUM BY THE *COSMIC BACKGROUND EXPLORER* (*COBE*)[1] SATELLITE

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ABSTRACT

We present a preliminary spectrum of the background radiation between 1 and 20 cm^{-1} (1 cm to 0.5 mm wavelength) from regions near the north Galactic pole, as observed by the FIRAS instrument on the *COBE* satellite. The spectral resolution is 1 cm^{-1}. The spectrum is well fitted by a blackbody with a temperature of 2.735 ± 0.06 K, and the deviation from a blackbody is less than 1% of the peak intensity over the range 1–20 cm^{-1}. These new data show no evidence for the submillimeter excess previously reported by Matsumoto *et al.* in 1988 in the cosmic microwave background. Further analysis and additional data are expected to improve the sensitivity to deviations from a blackbody spectrum by an order of magnitude.

Subject heading: cosmic background radiation

I. INTRODUCTION

The cosmic microwave background radiation (CMBR) dominates the total radiation density of the universe, but its spectrum has been exceptionally difficult to measure without systematic errors. The Far InfraRed Absolute Spectrophotometer (FIRAS) on the *COBE* satellite (Mather 1982; Gulkis *et al.* 1990) has been designed to measure extremely small deviations (0.1%) of the CMBR from a blackbody spectrum. It improves upon previous measurements in reducing the potential contributions of the systematic errors by (1) operating outside the atmosphere; (2) providing full aperture *in situ* calibration; (3) providing a continuous differential comparison with a reference blackbody adjusted to null the input signal; (4) operating the entire instrument, including the beam forming optics, in a well-shielded environment at cryogenic temperatures; and (5) using an improved horn antenna with a flared aperture to define the beam and reduce the radiative contributions from objects outside the main beam.

The standard hot big bang model has large enough photon creation and destruction rates to thermalize the early universe until it was about 1 yr old ($z > 10^6$). In later epochs, energetic processes may no longer be thermalized, leading to deviations of the CMBR spectrum from a blackbody shape (Peebles 1971). Such distortions, if present even at extremely low levels, can be used to determine the physical conditions in the early universe including estimates of the inhomogeneity, the energy release in galaxy formation, and the development of large-scale structure. Early energy release ($4 \times 10^4 < z < 10^6$) would produce a Bose-Einstein distribution with a nonzero chemical potential μ. Later energy release would produce a Comptonized spectrum, equivalent to a linear superposition of blackbodies at different temperatures, characterized by a y parameter, where y is an integral of the electron pressure (Zel'dovich and Sunyaev 1969). An optically thin hot intergalactic medium, or an interstellar or intergalactic dust distribution, could add its own characteristic spectrum.

II. INSTRUMENTATION

The FIRAS is cooled to a temperature of 1.5 K by a liquid helium cryostat similar to that used on the *Infrared Astronomical Satellite* (*IRAS*). The FIRAS is a rapid-scan polarizing Michelson interferometer similar to earlier balloon and rocket instruments (Woody *et al.* 1975; Woody and Richards 1981; Gush 1981), but with several improvements. A simplified sketch of the optical concept is given in Mather (1982) and in Gulkis *et al.* (1990). The area-solid angle product $A\Omega$ is large (1.5 cm^2 sr) for high efficiency, and the instrument operates over a frequency range of 1–100 cm^{-1}. Two stroke lengths are available with maximum optical path differences of 1.2 and 5.8 cm. Beam divergence within the instrument limits the spectral resolution to 1%. Two scan speeds are available, giving 0.8 and 1.2 cm s^{-1} rate of change of the path difference, to help distinguish between instrumental errors and sky signals.

The instrument is a symmetrical four-port device. The modulated power appearing at either output port is proportional to the Fourier transform of the difference spectrum between the two input ports. One input port receives power from the sky through a compound parabolic concentrator which defines a 7° beam on the sky. This sky horn has a smoothly flared aperture to reduce diffractive sidelobes over a wide frequency range (Mather, Toral, and Hemmati 1986). The second input port views a temperature-controlled internal blackbody calibrator through a reference horn which is closely matched to the sky horn. Both outputs of the interferometer

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are used, with each output divided into a high-frequency (>20 cm^{-1}) and a low-frequency channel using dichroic beam splitters. The data for this *Letter* come from the more sensitive of the two low-frequency channels.

A significant advance over the previous instruments is the availability of a movable high-precision external blackbody calibrator which can be used in flight. When activated, the external calibrator replaces the sky input with a temperature-selectable blackbody with calculated effective emissivity ≥ 0.999, based on measured material properties and the optical design. The calibrator is a folded cone with the shape of a trumpet mute, made of Eccosorb CR-110 (Hemmati, Mather and Eichhorn 1985), with a 25° included angle. This geometry guarantees that any ray received by the spectrometer undergoes at least seven specular reflections from the Eccosorb. The effective emissivity is further increased by placing the calibrator in the highly reflective cavity formed by the sky horn.

Temperature gradients within the external and internal calibrators are minimized by heating each one only at its single point of mechanical support. The internal calibrator temperature is measured by two germanium resistance thermometers (GRTs) and controlled by a third. The external calibrator temperature is measured by three GRTs and controlled by a fourth. The scatter among the readings of these GRTs is 9 mK (1 σ) for the internal calibrator and 3 mK (1 σ) for the external calibrator, when these bodies are set at 2.7 K. Each horn has two thermometers, which agree much better than the calibrator thermometers. The thermometers were calibrated to 1 mK accuracy against NBS transfer standards, so a physical explanation of the scatter is required. Pending further analysis of possible electronic, thermal, and software causes, we are using a conservative error band of ± 0.06 K. While thermometric calibration questions dominate other uncertainties in this measurement of the absolute temperature of the sky, deviations of the *shape* of the spectrum from that of a blackbody can be determined with much greater accuracy.

The four detectors are composite bolometers with electrical NEP of the order of 4×10^{-15} W/$\sqrt{\text{Hz}}$ (Serlemitsos 1988). The operating temperature of the bolometers is 1.5 K.

III. OBSERVATIONS

The *COBE* was launched into a 99° inclination, 900 km altitude orbit with a 6 PM ascending node at 1434 UT on 1989 November 18. In this orbit, the spin axis of the *COBE* can be maintained pointing away from Earth and 94°.5 from the Sun. A large conical sunshade protects all the *COBE* instruments from direct solar and terrestrial radiation. The FIRAS looks out along the spin axis of the *COBE*, scanning a circle in the sky 94°.5 away from the Sun. As Earth moves during the year, this scanned circle will precess so that the FIRAS beam covers the entire sky in 6 months. The first in-flight calibration with the external calibrator was performed 1989 December 19–21.

Figure 1 shows averages of 10 interferograms obtained during two separate scans of the same region of the sky, with the internal calibrator set at indicated temperatures of 2.759 K and 2.771 K. It also shows an in-flight calibration interferogram obtained with the external calibrator at 2.750 K and the internal calibrator at 2.759 K. All of these data were taken with the reference horn and the sky horn temperatures set to 2.700 K.

The sky data reported in this *Letter* were taken in 9 minutes, using the short stroke length and slow scan speed, along the arc $(l, b) = (112°, 65°)$ to $(231°, 79°)$, with the center of the arc at $(l, b) = (137°, 79°)$. The data were taken while the spacecraft was outside known regions of high trapped particle fluxes. The interferograms are averaged together after eliminating recognizable spikes caused by cosmic-ray impacts on the detectors. Residuals from the subtraction of these spikes are not a major contributor to the uncertainties in the derived spectra. The details of the procedure for processing the interferograms are embodied in a carefully tested set of computer programs which will be documented in a future publication.

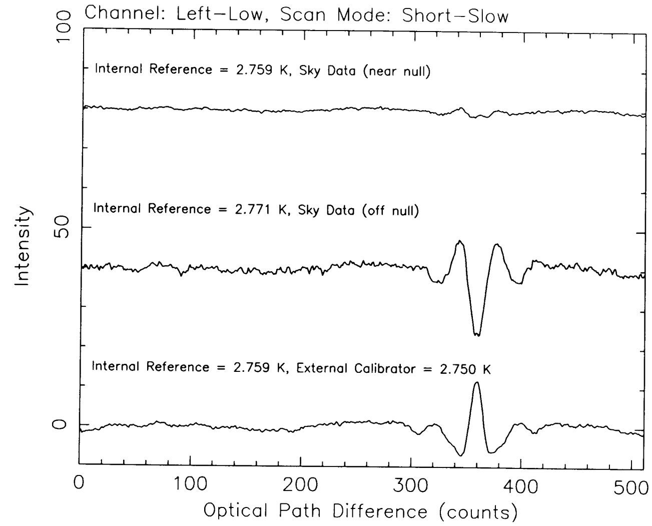

FIG. 1.—Raw co-added interferograms obtained from the FIRAS instrument in flight. *Top:* Sky near null condition, internal reference at 2.759 K; *middle*: sky slightly off-null, internal reference at 2.771 K; *bottom*: external calibrator at 2.750 K, internal reference at 2.759 K. See text for a discussion of thermometer accuracy.

The interferometer is calibrated using a linear photometric model to characterize the response of the instrument. The data for the model are produced by collecting interferograms with a range of temperatures for the two calibrators and the two horns on the input ports. This allows the effective emissivity of the horns and internal calibrator and the optical efficiency of the instrument to be determined at each frequency. The emissivity of the external calibrator is assumed to be unity for this model. The measured emissivities are approximately 0.0054 $\nu^{2/3}$ for both horns, where ν is in cm^{-1}, and 0.97 for the internal reference body, showing a well-balanced instrument. The residuals from the fit of these data to the linear model give an excellent assessment of the understanding of the instrument and the calibration. The residuals in the current model can be traced to small uncertainties in the thermometry of the calibrators and to uncertainties in the detector parameters used to account for small variations in their operating temperatures. The equations of Mather (1984) were used for these adjustments.

The uncertainty in the fit to this instrument model contributes a progressively smaller error as the offset between the two inputs is reduced. Ideally, in a perfect null setting of the instrument, one would need the knowledge of the instrumental gain factors only for determining the noise level. All the data presented in this letter represent interferograms made with offsets from null condition of less than 20 mK. If we conservatively estimate a calibration gain error of 5%, the resulting errors in the spectrum will be only 1 mK at all frequencies.

Figure 2 shows our preliminary measurement of the spectrum of the sky superposed on a 2.735 K blackbody curve.

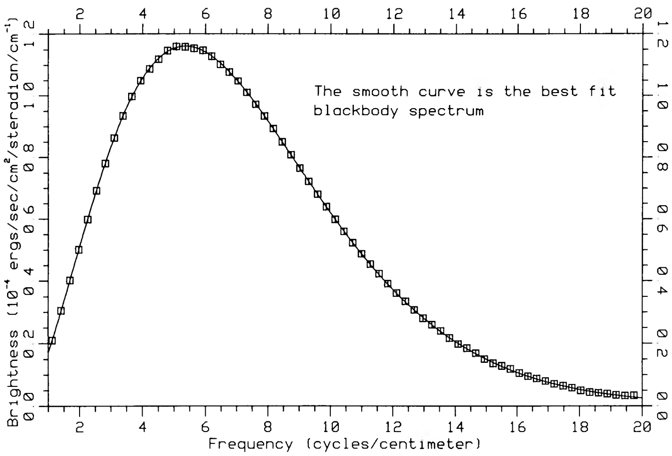

FIG. 2.—Preliminary spectrum of the cosmic microwave background from the FIRAS instrument at the north Galactic pole, compared to a blackbody. Boxes are measured points and show size of assumed 1% error band. The units for the vertical axis are 10^{-4} ergs s^{-1} cm^{-2} sr^{-1} cm.

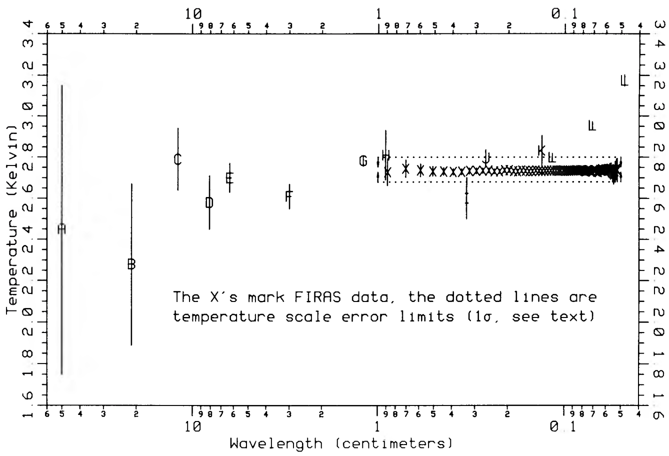

FIG. 3.—Composite plot of recent measurements of the temperature of the sky (temperature of the cosmic background vs. wavelength). A = Sironi *et al.* (1987), B = Levin *et al.* (1987), C = Sironi and Bonelli (1986), D = De Amici *et al.* (1988), E = Mandolesi *et al.* (1986), F = Kogut *et al.* (1988), G = Johnson and Wilkinson (1987), H = Smoot *et al.* (1985), I = Smoot *et al.* (1987), J = Crane *et al.* (1989), K = Meyer *et al.* (1989), Palazzi *et al.* (1990), L = Matsumoto *et al.* (1988).

The error band in Figure 2 is a conservative estimate of the systematic errors in our current calibration algorithm, taken to be 1% of the peak intensity of the spectrum. *Since the data show a good null both when the FIRAS is looking at the external calibrator and at the sky, one can determine from the interferograms alone that the spectrum of the sky is close to a blackbody, regardless of the details of the data reduction and calibration.*

IV. DISCUSSION

The CMBR temperature reported here lies between the average of direct ground-based measurements, 2.655 ± 0.036 K (see Smoot *et al.* 1988 for a tabulation), and the precise measurement of 2.783 ± 0.025 K ($1\ \sigma$) at 0.8 cm^{-1} made from a balloon by Johnson and Wilkinson (1987). At the CN transition frequency, the temperature measured by FIRAS is 2.735 ± 0.06 K, compared to 2.70 ± 0.04 K from Meyer and Jura (1985), $2.796(+0.014, -0.039)$ K from Crane *et al.* (1989), and 2.77 ± 0.4 K from Kaiser and Wright (1990). The FIRAS data are not consistent with the departures from a blackbody spectrum reported by Matsumoto *et al.* (1988).

Using the conservative 1% error bands, these new data set a $3\ \sigma$ upper limit on the Comptonization y parameter of 0.001 and on the chemical potential μ of 0.009. This value of μ is based on a fit to a pure Bose-Einstein spectrum with μ independent of frequency. The hot smooth intergalactic medium (IGM) suggested to explain the cosmic X-ray background by Field and Perrenod (1977), Guilbert and Fabian (1986), and recalculated by Taylor and Wright (1989) can be ruled out, since the predicted X-ray background scales as y^2. The new limits on y would limit the X-ray background to only 1/36 of the observed value, even at a heating redshift as small as $z_c = 2$. Many other sources of distortions of the CMBR spectrum (Bond, Carr, and Hogan 1986) are also severely constrained.

A more accurate determination of the spectrum will be made after further sky observations, calibrations, and refinement of the calibration algorithm. The ultimate accuracy of any measured spectrum distortions should be limited only by the optical design and stability of the external calibrator and by the models of radiation from interstellar dust.

It is a pleasure to acknowledge the vital contributions of all those at GSFC who devoted their efforts to making this challenging mission not only possible but enjoyable as well. Special thanks are due to Paul Richards and Patrick Thaddeus for their early encouragement to the lead author, to Robert Maichle and Michael Roberto for leading the engineering effort on the FIRAS instrument, and to Shirley Read, Robert Kummerer, and Leonard Olson for their leadership in software development for the FIRAS.

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