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THE SPECTRAL RESULTS OF THE FAR-INFRARED ABSOLUTE SPECTROPHOTOMETER INSTRUMENT ON *COBE*

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ABSTRACT

The cosmic microwave background (CMB) spectral results of the Far-Infrared Absolute Spectrophotometer (FIRAS) instrument are summarized. Some questions that have been raised about the calibration accuracy are also addressed. Finally, we comment on the potential for major improvements with new measurement approaches. The measurement of the deviation of the CMB spectrum from a 2.725 ± 0.001 K blackbody form made by the *COBE*-FIRAS could be improved by nearly 2 orders of magnitude.

Subject headings: cosmic microwave background — cosmology: observations

1. INTRODUCTION

The *Cosmic Background Explorer* (*COBE*) satellite was launched on 1989 November 18 (Boggess et al. 1992) with the Far-Infrared Absolute Spectrophotometer (FIRAS), DIRBE (Diffuse Infrared Background Experiment), and DMR (Differential Microwave Radiometer) instruments on board. With 10 months of cold operation and 4 yr of total operation, *COBE* provided a new view of the cosmic microwave and infrared radiation. Many papers have been written citing the results of the *COBE* mission; however, many authors have not recognized that the final results of the FIRAS were published in a technically oriented calibration paper (Mather et al. 1999).

The FIRAS instrument (Mather et al. 1990) covers the wavelength range from 100 μm to 1 cm, with reduced efficiency at short wavelengths. The maximum path difference of 58.5 mm yields an apodized spectral resolution of 0.4538 cm^{-1}. The FIRAS is a differential instrument, with two nearly equivalent input ports and two output ports. It has two frequency ranges (1–20 and 20–100 cm^{-1}). Its four semiconductor bolometer detectors are measured with DC bias and junction field effect transistor (JFET) preamplifiers, with sensitivities of the order of a few times 10^{-15} W $\mathrm{Hz}^{-1/2}$.

2. FIRAS RESULTS

The FIRAS data were collected from four detectors operating in two different scan modes. The FIRAS Pass 4 (Brodd et al. 1997)[3] data include all of the detectors and modes. The detectors and modes have been cross-checked (Brodd et al. 1997) and checked against both the DMR data (Fixsen et al. 1997a) and the DIRBE data (Fixsen et al. 1997b) and shown to be consistent with them in the areas of overlap.

These are the final data, and they are available from the National Space Science Data Center (NSSDC). The NSSDC also provides detailed explanatory material on the instrument, the data processing, and the calibration model.

2.1. *CMB Temperature*

Three independent estimates of the CMB temperature were made from the FIRAS data (Mather et al. 1999). The first uses three thermometers, discussed by Fixsen et al. (1994), with a 5 mK readout correction due to the readout current heating the thermometer, as discussed by Mather et al. (1999). This approach yields a temperature of 2725.0 ± 1.0 mK, with the uncertainty dominated by the absolute calibration of the thermometers.

A second independent temperature estimate relies on the frequencies of Galactic CO emission to set the frequency scale and the "color" of the spectrum to determine its temperature, resulting in a temperature of 2725.5 ± 0.85 mK. The uncertainty is dominated by the frequency determination (Fixsen et al. 1996).

A third independent temperature estimate relies on the spectrum of the dipole and its amplitude, as determined by the DMR instrument, which was independently calibrated. This results in a temperature estimate of 2722 ± 12 mK (Mather et al. 1999).

These three temperature estimates can be formally summed to 2725.28 ± 0.65 mK, but to be conservative, we advise using 2725 ± 1 mK. This is in agreement with the DMR result of 2725 ± 20 mK (Lineweaver et al. 1996), using the motion of the Earth.

2.2. *CMB Spectral Distortions*

The FIRAS measurements indicate that the limits of the Bose-Einstein and Compton distortions are $|\mu| < 9 \times 10^{-5}$ (95% CL) and $|y| < 15 \times 10^{-6}$ (95% CL) (Fixsen et al. 1996). The uncertainties are dominated by the noise of the calibration data, which were taken only about 10% of the total time.

The μ parameter describes a distorted blackbody with a chemical potential, possibly the result of energy added to the CMBR during a time when photon energy redistribution by electron scattering is rapid but the photon number is effectively fixed. The y parameter describes a mix of blackbody spectra at different temperatures, as might occur from scattering of anisotropic radiation, or from second-order effects like the Sunyaev-Zel'dovich effect in Galaxy clusters. The final monopole spectrum is thus well modeled by a 2.725 K $\pm$ 1 mK blackbody. The measured deviations from this spectrum are 50 parts per million (ppm, rms) of the peak brightness of the CMBR spectrum, within the uncertainty

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of the measurement. Wright et al. (1994) showed that the measured limits on distortion of the CMBR spectrum imply a strict limit of $\Delta U/U < 7 \times 10^{-5}$ on the amount of energy added to the CMBR after the first year of the big bang. Such energy might conceivably have come from the decay of long-life elementary particles, or from the conversion of turbulent energy due to the initial conditions of the big bang.

It is sometimes stated that this is the most perfect blackbody spectrum ever measured, but the measurement is actually the difference between the sky and the calibrator. It does not determine whether Planck's formula is correct at the same level of precision. This measurement allows the blackbody spectrum to be different from the Planck function as long as *both* the sky and the calibrator have very nearly the same spectrum. On the other hand, large deviations from the Planck function can be excluded on the basis of the self-consistency of the calibration data alone, which were taken at many different temperatures and frequencies.

2.3. *Dipole*

We have recomputed the dipole term of the CMB brightness, using the final best value of the adjusted temperature of 2.725 K. Our previous result was described by Fixsen et al. (1996) and used the estimated temperature of 2.728 K. The new result is a dipole amplitude of 3.381 ± 0.007 mK or a velocity of 372 ± 1 km s^{-1} in the direction $l = 264\fdg14 \pm 0\fdg15$, $b = 48\fdg26 \pm 0\fdg15$. This is in close agreement with the DMR result (3.358 ± 0.023 mK toward $264\fdg31 \pm 0\fdg17, 48\fdg05 \pm 0\fdg10$) from Lineweaver et al. (1996). The uncertainty is dominated by the removal of the Galactic dust radiation.

2.4. *Anisotropy*

The FIRAS data were analyzed to compare with the anisotropy measurement of DMR (Bennett et al. 1996). The FIRAS quadrupole result, $Q = 24.8 \pm 7.1$ μK (Fixsen et al. 1997a), has higher noise but agrees with the DMR result ($Q = 17.9 \pm 1.6$ μK). The FIRAS data also show that the anisotropy has roughly the expected blackbody spectrum (Fixsen et al. 1997a) with approximately the expected amplitude. The uncertainties are dominated by the noise of the FIRAS detectors.

2.5. *Cosmic Infrared Background*

The FIRAS data have been analyzed to determine the infrared background, first published by Puget et al. (1996). Fixsen et al. (1998) show that the infrared background can be characterized by $(1.3 \pm 0.4) \times 10^{-5}(\nu/\nu_0)^{0.64\pm0.12}$ $P_\nu(18.5 \pm 1.2\ \mathrm{K})$, where P is the Planck function. The uncertainty is dominated by the problem of separating the CIB radiation from the local Galactic dust radiation.

This result agrees with the DIRBE result (Hauser et al. 1998) in the region of overlap. The subject is treated extensively by Hauser & Dwek (2001) in a review paper. The intensity of this far-infrared background is larger than the visible and near-infrared light of all the cataloged galaxies, implying that at least half of all the light of stars and active galactic nuclei has been absorbed by dust and reradiated in the far-infrared.

2.6. *Galaxy Emission*

Although not designed specifically for line detection, the full-sky coverage and careful calibration allowed detection of many Galactic emission lines, including [C II], [C I], [N II], CO, H_2O, [O I], and CH (Fixsen, Bennett, & Mather 1999). Although the FIRAS does not have high-frequency resolution, the rotation of the Galaxy is detectable in the Doppler shift of the brightest lines (Fixsen et al. 1996). There is even evidence of the water line at 269 μm, seen in absorption against the Galactic center. The interpretation of these lines has been approached by Petuchowski & Bennett (1995). Everywhere except the Galactic center, the uncertainty is limited by the noise of the FIRAS detectors.

Schlegel, Finkbeiner, & Davis (1998) treat the Galactic dust using the FIRAS Pass 4 data, along with the *IRAS* and DIRBE data. They estimate the temperatures and dust densities and produce a map and model of the dust. They use their approach to estimate the cosmic infrared background intensity as well. Their excellent estimation of reddening, high spatial resolution (from *IRAS*), and wide bandwidth (from FIRAS and DIRBE) must be treated with a note of caution. The high resolution at long wavelengths is an extrapolation. In particular, hot stars in dust clouds generate bright concentrations at 100 μm that are not continued to longer wavelengths dominated by cooler dust.

2.7. *Zodiacal Dust Emission*

The spectrum of the zodiacal emission shows a break in slope near 150 μm (Fixsen & Dwek 2002), which shows that the typical zodiacal dust particles are smaller than about 50 μm, with a significant fraction about 30 μm in radius. This result requires the long-wavelength coverage of FIRAS and was not recognizable with the DIRBE data alone.

3. CALIBRATION

There are several papers (Giorgi 1995; Battistelli, Fulcoli, & Macculi 2000; Salvatera & Burigana 2002) that question the FIRAS calibration. Here we address these calibration issues.

Giorgi (1995) suggested that there might be an asymmetry of 5% in the two input arms of the FIRAS, although the measured asymmetry is only 1%–3% (depending on the frequency) referred to the external calibrator (XCAL). It was measured to $\sim$0.01% precision by the calibration process, and radiation (or lack thereof) from the bolometer itself makes up most of the difference. In any case, this number does not enter the calculation of the accuracy of the XCAL, since the ultimate accuracy depends only on matching the XCAL to the sky.

Battistelli et al. (2000) used the reflectance of the Eccosorb and an approach to physical optics to estimate a raw emissivity of 0.998 for the XCAL at long wavelengths. Salvatera & Burigana (2002) then use these results to suggest that distortions to the CMB might be larger than the reported limits.

The calibration was treated thoroughly by Fixsen et al. (1994). To address the questions that have been raised, we summarize only a few key aspects of the calibration. The first key point is that the measurement is the comparison of the sky with an ideal movable external blackbody calibrator (XCAL) that can fill the aperture of the sky horn. The rest of the calibration process is used to measure gains and offsets that apply if the calibrator spectrum does not match the sky spectrum.

A second key idea is that a Kirchhoff condition applies to the measured étendues, where an étendue is defined as an effective area–solid angle product coupling a radiation source to a detector. FIRAS detects only modulated signals, but these can have either positive or negative signs. The Kirchhoff condition requires that the sum of all the effective étendues is zero; in our notation, $\sum_k a_{fk} = 0$. This condition is the mathematical statement that the radiation falling on each detector comes from somewhere, and, since the detector remains unchanged, for any source eclipsed by the movement of the mirror transport mechanism, there is another source (or sources) that is uncovered by the same motion.

The two intended sources are the internal calibrator (ICAL) and the XCAL. Other sources considered are the sky horn, the reference horn, the moving dihedral mirrors (which modulate the interferometer path difference), the physical support structure, and the bolometer itself. The calibration model explicitly took these seven sources into account and derived their optical parameters a_{fk} from observations taken with many different combinations of temperatures from 2 to 20 K. The calibration model accounts for almost all of the changes in the interferograms as the calibrators and horns are heated individually and together.

The determination of the effective étendue of the physical structure and the bolometer relies on uncontrolled small variations in the temperature of each. Because both the bolometer and the structure remained below $\sim$2 K, the determination of these elements' effective étendues is unreliable at high frequency, but for the same reason, it is not required (their emission at high frequencies is negligible).

The FIRAS is absolutely calibrated by its external blackbody. If the spectrum of the sky can be duplicated when the XCAL is inserted in the horn at some temperature, then the sky has the same spectrum as the XCAL. The ICAL, the other parts, and the instrument calibration model merely serve as an elaborate transfer standard. This addresses Giorgi's point. Even if the two inputs are asymmetric, the asymmetry is the same whether observing the sky or the XCAL.

Thus, two questions are of paramount importance. First, what is the temperature of the XCAL and how well is it known? And second, how close is the spectrum of the XCAL to a blackbody?

To address the first question, the temperature of the XCAL was measured and controlled with four germanium resistance thermometers (GRTs) attached to the XCAL. The XCAL itself was designed to be isothermal (Mather et al. 1999), as there was no known source of significant heat flow through it. The GRTs were carefully calibrated against a National Institute of Standards and Technology standard to 1 mK accuracy. As a further check, 10 of the GRTs calibrated in the same batch as the flight GRTs were recalibrated 1.7 yr after launch (Mather et al. 1999).

Three of the thermometers were read out continuously during the 10 month flight, while the fourth was used in a feedback circuit to control the temperature. All of the calculations and data indicate that the XCAL was isothermal to $\sim$10 μK and that the temperature (after corrections) was known to 1 mK. The temperature itself was confirmed by the self-consistency of the calibration model, as described above, using the spectrometer to measure a color temperature based on the dependence of brightness on wavelength.

To address the second question, the XCAL is designed in the shape of a trumpet mute, to allow multiple reflections on the Eccosorb surface to increase its apparent emissivity. Halpern et al. (1986) made careful measurements of the reflection of Eccosorb at various frequencies, and these were used to predict the emissivity of the calibrator. The groove angle of 25° requires that a ray entering the calibrator parallel to the axis will be specularly reflected from the Eccosorb surface seven times before escape and, moreover, will return at an angle of 5° off-axis, which is outside the acceptance angle of the horn.

We also did a physical optics calculation, finding that the long-wavelength reflectance of the calibrator is due almost exclusively to scattering at the edge, where it meets the horn. In our opinion, the Battistelli et al. (2000) result must originate from the same location.

However, one must also consider the source of any reflection. The XCAL is part of a closed cavity composed of the calibrator, the sky horn, a small gap between the calibrator and the sky, and a small aperture leading to the spectrometer horn. Consequently, the radiation reflected by the calibrator must have originated from either itself, the sky horn, the sky through the gap, or the small aperture to the spectrometer. Three of these sources are effectively at the temperature of the CMB. As the most emissive of the four, the source of most of the reflected radiation is the calibrator itself. This reflected radiation from the calibrator increases the calculated effective emissivity of the calibrator from 0.998 to 0.99994 or a reflection of 6×10^{-5}. Battistelli et al. (2000) did not discuss this effect and drew an unnecessarily pessimistic conclusion. Moreover, since both the horn and the XCAL temperatures were set to match the CMB temperature, the only source of radiation that could be reflected by the calibrator and that was not at the CMB temperature is the small aperture leading to the spectrometer. The reflectance for radiation originating there is the only one that can produce an error in the blackbody spectrum of the calibrator.

More significantly, rather than depending on complex calculations, direct measurements were made of the reflection of a duplicate of the XCAL (the flight spare) in a duplicate of the sky horn (the flight spare). Measurements were made for a variety of tilts of the XCAL and for frequencies of 30–37 and 93.6 GHz (Mather et al. 1999). The largest reflection coefficient observed was 4×10^{-5} (at 35.25 and 36.86 GHz with the XCAL flat). Because the reflection for the FIRAS is averaged over wide frequency bands and many modes, the effective reflection is likely to be in the few times 10^{-6} range, which was the typical measured reflection. To be conservative, we use a limit of 3×10^{-5}.

4. FIRAS II

4.1. *Motivation*

With the improvements listed in § 4.2, we think that it should be quite feasible to measure the deviation of the CMB spectrum from a perfect blackbody form with an accuracy and precision of 1 ppm. Such an instrument could measure or provide upper limits on the cosmic y and μ parameters at the $\sim 10^{-7}$ level and provide a spectrum of the anisotropy to 10%.

There are many possible causes of distorted cosmic background spectra (Tegmark & Silk 1995). The more radical ideas have already been ruled out by the FIRAS data, but attenuated versions of them may still be viable. These include: (1) The dissipation of gravity waves, turbulent energy, or inhomogeneity in the early universe. While inflationary predictions are in good agreement with the anisotropy and spectrum observations, small but uniform additions to the energy of the CMB field might still be hidden from us. The behavior of the dark matter as it clumps might not be so innocent, as is generally assumed. (2) Slight nonequilibrium behavior at the decoupling, due to the optical thickness of the Lyα line or the presence of small concentrations of LiH or H_2D^+ molecules (Dubrovich & Lipovka 1995). (3) The decay of unstable particles, or the conversion of dark matter particles or energy to ordinary energy. There is so far no reason to expect them, but the work of elementary particle physics is still not finished. (4) The unknown effects of dark energy or quintessence fields. (5) The general Sunyaev-Zel'dovich effect, accumulated from all the Galaxy clusters and hot intergalactic medium (Cooray, Hu, & Tegmark 2000). (6) The effects of reionization, perhaps at a redshift of 6–30 (Yamada & Fujita 2001). (7) Unexpectedly dusty early galaxies, with dust barely above the blueshifted CMBR temperature of $2.7(1+z)$ K (Aghanim, Balland, & Silk 2000).

The understanding of the foreground emission from the Galactic dust limited several measurements (but not the distortion). Only the simplest single parameter fit was required to reduce the dust contamination of the CMB spectrum to below the noise of the FIRAS detectors. On measurements more sensitive to the dust (e.g., CIB), a two-component model of the Galactic dust was required. In regions outside of the Galactic plane, the two-component model is all that was required to reduce the Galactic signal to below the noise of the FIRAS instrument. While not trivial, a more detailed model could be developed with higher signal-to-noise data. This more detailed model might still be the limiting factor in determining the CMB spectrum, but this should be at least an order of magnitude below the simple one-parameter model, which is not the limiting accuracy for FIRAS. This would allow at least an order-of-magnitude improvement on the cosmic distortion parameters and perhaps as much as a factor of 50.

In the process, the improved instrument would also provide maps of many components of the interstellar medium: dust of several types and temperatures could be recognized, the atomic and molecular lines could be mapped with precision, and at long wavelengths the contribution of Galactic synchrotron and free-free emission might be directly detectable even at the relatively short wavelengths of an infrared instrument. Improved sensitivity, combined with the ability to point the instrument at selected objects, would also permit concentrated observations of external galaxies and galaxy clusters (Colafrancesco et al. 1997). As the spectra and spatial distributions of these foreground objects are quite different over the wide spectral range of the FIRAS, it would be possible to separate their contributions in data analysis, leading to a precisely measured residual cosmic background radiation spectrum.

Improved sensitivity might allow detection of the metals from Population III stars (Rowan-Robinson, Negroponte, & Silk 1979).

4.2. *Technical Approach*

Before considering how improvements might be made over the FIRAS instrument, it is worth looking at some of the limitations of the FIRAS instrument.

One of the major limitations was the effect of cosmic rays. The residual noise (after deglitching) of cosmic rays dominated the noise of the FIRAS instrument. The problem was compounded by co-adding 16 scans before relaying the data to the ground (due to a limitation of onboard memory and downlink capability). This had the effect of contaminating 16 samples and simultaneously reducing, by a factor of 4, the signal-to-noise ratio available to remove the glitches. By eliminating the on-board co-add process (or applying deglitching before co-adding), the glitch contamination could be reduced by a factor of 16. By reducing the size of the detectors by a factor of 3–4, an equivalent reduction of glitch rate is easily achieved. By using "spiderweb" bolometers (Mauskopf et al. 1997) or antenna-coupled microbolometers, a further significant reduction could be achieved. Finally, the remaining glitches can be more easily removed, since their effect is not diluted and the noise of modern bolometers is much less than those from $\sim$1974.

A low-noise bolometer would probably need to run well below 1 K. However, the required temperatures can easily be achieved with He^3 or adiabatic magnetization refrigerators.

Harmonics due to internal reflections introduced significant signals at higher frequencies. The major problem here was the reflection ($\sim$3%) from the ICAL. By using the same design as the XCAL, this can be reduced by 2 orders of magnitude.

There were annoying vibrations at 57 and $\sim$8 Hz. These can be eliminated by stiffening the mirror support structure to move the vibration out of the signal band and not using a phase-lock loop in the mirror control loop.

Another limitation was the read noise on the thermometers ($\sim$4 mK) and the absolute accuracy of these thermometers. Simple circuits (Fixsen et al. 2002) with RuO sensors can reduce the read noise to 0.1 mK while maintaining the low power required to not heat the object under investigation. By observing the interstellar CO lines (or other lines), the absolute frequency and absolute temperature scale can be established, as demonstrated with FIRAS.

Thus, one can contemplate what a new version of the FIRAS might look like. Deep-space environments like the Sun-Earth Lagrange point (L2) are routinely planned for missions that would be adversely affected by proximity to the Earth. It has also been recognized that instruments are no longer limited to the size of their cryostats, if they can be cooled after launch. Microwave technology has also improved, leading to plans for precise measurement of the CMB temperature at wavelengths out to 30 cm (Kogut 1996).

We still recommend the choice of a Michelson interferometric spectrometer, for many reasons relating to its differential nature, its ability to handle large étendues, and the operator's control of the spectral response function.

We would consider pointing horns at a parabolic reflector (0.5–1 m) to obtain a smaller beamwidth (1°–2°), but this requires careful analysis of the effects of beam spillover and excellent control of stray light from any warm parts of the observatory. Although not strictly required for the spectrum measurement, a smaller beam on the sky allows more pixels to compare for Galactic radiation removal, reduce the fraction of the sky seriously contaminated by Galactic radiation, and add valuable information about the Galaxy and the anisotropy. Finally, by operating at the L2 point of the Earth-Sun system, the instrument needs much less shielding from the Earth.

To calibrate such a system would still require a complete measurement of all radiation that could enter the instrument, so a large closed structure to emulate the FIRAS calibrator-horn combination would be required. For example, we would surround the entire optical system with segmented blackbody radiators to measure the sidelobe responses and ensure that the source of every photon is understood. While large and awkward, such a calibration system is not infeasible and could still reach extreme accuracy through control of all temperature gradients.

Alternatively, one might use small calibrators on the feed horns and measure the emission from the parabolic mirrors by heating them to $\sim$25 K.

Modern interferometer designs include several ways to make the instrument nearly immune to alignment errors, using cube corners or other retroreflectors instead of the dihedral mirrors that FIRAS used to rotate the polarization state. Modern designs also use focusing optics to reduce the size of the beam splitters to a much more manageable size. Both of these improvements would enable superior optical performance for the interferometer.

The FIRAS wavelength range was limited on the long side by its étendue to $\lambda < 1$ cm. By using smaller detectors, a new instrument might be limited to $\lambda < 0.5$ cm. The FIRAS wavelength range was limited on the short side by the beam splitters. Beam splitters with higher wire density are now commercially available. A new instrument could thus increase the useful band to somewhat shorter than 100 μm.

The calibration accuracy could be improved by different choices in the calibrator design. In the case of FIRAS, there was a significant concern about heat from the spacecraft's sunshield that might impinge on the calibrator support arm, necessitating a different thermal design for the calibrator itself. There was also concern that some of this heat might bounce off the support arm and through the gap between calibrator and horn, although there was no evidence of such a path in the flight data.

The largest uncontrolled and imperfectly measured effect that limited the FIRAS calibration accuracy was the calibrator reflectance of light that originated (or failed to originate) in the instrument volume and was transmitted up the sky horn toward the calibrator. Our calculations showed that most of this reflectance is due to diffraction at the junction between the calibrator and the horn. With a new design, it would be possible to make this occur at a spot that is not visible to the detectors, attenuating the error by orders of magnitude. This effect could be measured directly with shutters and heated blackbodies and beam splitters shining radiation up toward the calibrator. It could also be largely eliminated by heating the instrument chamber, with all its optics and support structures, to the same temperature as the calibrator and horn. Only the detectors need to be at temperatures different from 2.725 K. To measure the radiation originating at the detectors, one of the detectors could be heated to detect its effect on the other detector, and vice versa. This effect was too small to measure in the FIRAS data.

We recommend that a future instrument be built in a completely symmetrical way. The next-generation instrument should have two identical inputs, each with its own movable external calibrator and sky horn. To fully utilize the symmetry, one-fourth of the data should be taken in each of four modes: both calibrators in, both out, one in, and the other one in. This allows checking the calibrators against each other as well as against the sky and enables an end-to-end system calibration and performance test before launch, something that was not possible for the FIRAS.

Improved detector characterization is also possible. The FIRAS took data in only one direction of the stroke, but to fully characterize the detectors, data should be taken in both directions of the scan. With computer control, the scan length could be varied from scan to scan, enabling a search for any errors that relate to the exact length of stroke. This would also allow for the necessary apodization to happen at the data collection time, optimizing the observing efficiency. An apodized symmetric scan pattern would allow systematic detection and correction at a deeper level into the already lower noise of the detectors.

In the case of the FIRAS, only 10% of the total observing time was devoted to calibration data. This choice limited the calibration accuracy because detector noise was the dominant limiting factor. With new detectors, it might be possible to reach the systematic error limits much more quickly. Ideally, these limits would also be reduced by better calibration design.

To give some numerical appreciation for the concepts described above, we give some key parameters. The frequency coverage would be from 2 to 120 cm^{-1} (60–3600 GHz), the étendue would be about 0.45 cm^2 sr, the resolution would be about 0.2 cm^{-1} (6 GHz), and the beam splitters would have 4 μm gold wires on a Mylar substrate with 10 μm spacing, with an effective mirror stroke of 265 mm based on a 75 mm physical motion. The beam divergence (in the Fourier spectrometer) would be $\pm 6^\circ$, with an f/5 beam of diameter 42 mm. The beam divergence limits the spectral resolution to $R = \nu/\Delta\nu < 200$. It is not practical to obtain a beam diameter on the sky much less than the FIRAS design of 7° without the use of an external parabolic mirror, so we would provide a 1 m aperture off-axis parabolic mirror surrounded by absorbing walls of controlled temperature. Using the central 0.42 m for the geometrical optics beam, this would provide a beam width on the sky of $1\overset{\circ}{.}2$. The remainder of the parabolic aperture would be a "guard ring" to ensure that the beam spillover onto the black walls is extremely small. The detectors would be four spiderweb bolometers, one for each polarization, with two on each side. With reasonable optical efficiencies (10%), each bolometer would achieve a cosmic background photon noise-limited sensitivity (noise-equivalent power, NEP) of a few times 10^{-17} W $\mathrm{Hz}^{-1/2}$, about 100 times better than that obtained for FIRAS. This is enough to meet the goal of seeing deviations from the pure blackbody form of spectrum that are a few parts in 10^7.

None of the improvements discussed here are beyond the current state of the art for space flight. The most difficult would be the demonstration of calibration accuracy with a parabolic mirror to reduce the beamwidth, since that requires much larger hardware than the concentrators used for FIRAS. We conclude that a combination of improved detectors and improved designs could enable a much more precise measurement of the CMBR spectrum distortion, capable of reaching the astrophysical limits set by our location in the Galaxy.

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REFERENCES

Aghanim, N., Balland, C., & Silk, J. 2000, A&A, 357, 1
Battistelli, E. S., Fulcoli, V., & Macculi, C. 2000, NewA, 5, 77
Bennett, C. L., et al. 1996, ApJ, 464, L1
Boggess, N. W., et al. 1992, ApJ, 397, 420
Brodd, S., Fixsen, D. J., Jensen, K. A., Mather, J. C., & Shafer, R. A., eds. 1997, COBE FIRAS Explanatory Suppl. (COBE Ref. Publ. No. 97-C; Greenbelt: NASA/GSFC)
Colafrancesco, S., Mazzotta, P., Rephaeli, Y., & Vittorio, N. 1997, ApJ, 479, 1
Cooray, A., Hu, W., & Tegmark, M. 2000, ApJ, 540, 1
Dubrovich, V. K., & Lipovka, A. A. 1995, A&A, 296, 301
Fixsen, D. J., Bennett, C. L., & Mather, J. C. 1999, ApJ, 526, 207
Fixsen, D. J., & Dwek, E. 2002, ApJ, 578, 1009
Fixsen, D. J., et al. 1994, ApJ, 420, 445
———. 1996, ApJ, 473, 576
———. 1997a, ApJ, 486, 623
———. 1997b, ApJ, 490, 482
———. 1998, ApJ, 508, 123
———. 2002, Rev. Sci. Instrum., 73, 3569
Giorgi, P. G. 1995, Infrared Phys. Tech., 36, 749
Halpern, M., et al. 1986, Appl. Opt., 25, 565
Hauser, M. G., & Dwek, E. 2001, ARA&A, 39, 249
Hauser, M. G., et al. 1998, ApJ, 508, 25
Kogut, A. 1996, in Proc. XVI Moriond Astrophysics Meeting (astro-ph/9607100)
Lineweaver, C. H., et al. 1996, ApJ, 470, 38
Mather, J. C., et al. 1990, ApJ, 354, L37
———. 1999, ApJ, 512, 511
Mauskopf, P. D., Bock, J. J., Del Castillo, H., Holzapfel, W. L., & Lange, A. E. 1997, Appl. Opt., 36, 765
Petuchowski, S. J., & Bennett, C. L. 1995, ApJ, 438, 735
Puget, J. L., et al. 1996, A&A, 308, L5
Rowan-Robinson, M., Negroponte, J., & Silk, J. 1979, Nature, 281, 635
Salvatera, R., & Burigana, C. 2002, MNRAS, submitted (astro-ph/0203294)
Schlegel, D. J., Finkbeiner, D. P., & Davis, M. 1998, ApJ, 500, 525
Tegmark, M., & Silk, J. 1995, ApJ, 441, 458
Wright, E. L., et al. 1994, ApJ, 420, 450
Yamada, M., & Fujita, Y. 2001, ApJ, 553, L145