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The COBE Experience

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COBE-Preprint-No-93-10B

ABSTRACT

The COsmic Background Explorer, (*COBE*), launched on 18 November 1989, made all-sky surveys in the millimeter, sub-millimeter, and infrared bands, with the goal of detecting and studying the Cosmic Infrared Background (CIB), and of making detailed studies of the Cosmic Microwave Background (CMB). Since these backgrounds come to us from redshifts z ranging from a few to 10^3, corresponding to co-moving distances of $(54 - 360) \times 10^{24}$ meters. *COBE* is certainly doing the most remote of all the "remote sensing" discussed in this session.

1. Introduction

The origin of the *COBE* mission goes back to 1974 when NASA issued Announcements of Opportunity (AO-6 and AO-7) for new Explorer class space missions. Three proposals suggesting CMB studies were combined into a single study team. I joined this study team in 1978. The *COBE* mission is the product of many years of work by a large team of scientists and engineers. Credit for all of the results presented in these lectures must be shared with the other members of the the *COBE* Science Working Group: Chuck Bennett, Nancy Boggess, Ed Cheng, Eli Dwek, Sam Gulkis, Mike Hauser, Mike Janssen, Tom Kelsall, Phil Lubin, John Mather, Steve Meyer, Harvey Moseley, Tom Murdock, Rick Shafer, Bob Silverberg, George Smoot, Rai Weiss, and Dave Wilkinson. Bennett *et al.* is an excellent review[1] of the history of the *COBE* project and its results up to the discovery of the anisotropy of the CMB, but not including the latest limits on distortions of the spectrum of the CMB.

One part of the *COBE* experience should be kept in mind by anybody planning a space mission: it took 15 years from proposal to launch even for an Explorer, which is supposed to be a small fast experiment. In fact the Extreme UltraViolet Explorer, *EUVE*, which was launched in June 1992, and the yet to be launched X-ray Timing Explorer, *XTE*, were also selected from the proposals responding to AO 6 & 7 in 1974. This 20 year queue has been a very discouraging aspect of space astrophysics. Certainly part of the reason for the long delay between selection and launch for *COBE* was to see whether the porous plug used in the *IRAS* dewar would in fact allow superfluid liquid helium to be used in space. During this long wait in line, *COBE* went from a Delta launch to a shuttle launch and then back to a Delta launch. The shuttle version of *COBE* needed to carry a ton of hydrazine to reach the required altitude, as well as a bigger and heavier structure to carry both launch and abort landing loads. Furthermore, the shuttle's

projected payload capacity for polar orbits was quite low. As a result, the shuttle version of *COBE* used about 90% of the payload capacity. After the Challenger explosion in 1986 it became clear that the shuttle would never be launched into a polar orbit, and *COBE* was rebuilt for a Delta launch. Over 54% of the mass was eliminated with no loss of scientific capability.

COBE carries three instruments: the DIRBE, or Diffuse InfraRed Background Experiment; the DMRs, or Differential Microwave Radiometers, and the FIRAS, or Far InfraRed Absolute Spectrophotometer. The DMR instrument is attached to the outside of the dewar, while the DIRBE and FIRAS instruments are in the liquid-helium dewar operating at 1.5 K. The three separate boxes of the DMR operate at the three frequencies of 31.5, 53 and 90 GHz. The 53 and 90 GHZ radiometers use HEMT IF amplifiers that operate at 150 K, while the 31 GHz radiometer operates at 300 K. The DMRs do not require cryogenic cooling. The DIRBE is a 19 cm diameter off-axis Gregorian telescope that measures the flux within a 0.7° square field-of-view. A tuning fork chopper is used to switch between the sky and the 2 K DIRBE cavity (a zero reference at all DIRBE bands) at a 32 Hz rate. Simultaneous measurements are made in 10 bands: the J, K, L and M bands of ground-based IR photometry at 1.25, 2.2, 3.5 and 4.9 μm, the four *IRAS* bands at 12, 25, 60 and 100 μm, and two long wavelength bands at 140 and 240 μm. The FIRAS is a polarizing Michelson interferometer[2] covering the range from 100 μm to 1 cm.

2. COBE Orbit and Attitude

COBE is in a sun-synchronous polar orbit with a 99° inclination and a 900 km altitude. The ascending node occurs at 6 PM local time, and the inclination is chosen to give a precession rate of 360° per year, which gives a fixed local time for the ascending node. The altitude of 900 km is a trade-off between residual atmosphere which could contaminate the cryogenic optics on *COBE*, and the effects of high energy protons and electrons trapped in the Earth's magnetosphere. The basic attitude for *COBE* has the Sun 94° and the Earth 180° away from the center of the pattern of the instrument boresights. For this to work, the Earth-Sun line must be perpendicular to the orbit plane. A line drawn perpendicular to the orbit of *COBE* intersects the celestial sphere at ±9° declination, but at a right ascension that varies by one cycle per year. By launching to the South at dawn, the Sun is placed at the same right ascension as the end of the orbit normal at declination −9°, which means that at the June solstice the Sun is located 32° away from the perpendicular to the orbit. The depression of the horizon at 900 km altitude is 28°, so *COBE* is eclipsed for up to 20 minutes per orbit for a period of two months centered on the June solstice. These eclipses occur over the South Pole. During the same season the Earth limb rises several degrees above the plane of the Sun shade when *COBE* flies over the North Pole.

3. Cryogenic and thermal performance

With the interior of the Sun shade shielded from the Sun all the time and the Earth most of the time, radiative cooling led to a dewar outer shell temperature of 130 K. The temperature inside the dewar was 1.4 K until the superfluid helium was depleted 307 days after launch. Given the low outer

Reference	λ (μm)	λI_λ (10^{-7} W m^{-2} sr^{-1})	$T_B(\lambda)$ K
DIRBE	1.2	8.3 ± 3.3	351
(South Ecliptic Pole)	2.3	3.5 ± 1.4	216
	3.4	1.5 ± 0.6	140
	4.9	3.7 ± 1.5	109
	12.	29. ± 12	56
	22.	21. ± 8	34
	55.	2.3 ± 1	15
	96.	1.2 ± 0.5	9.2
	151.	1.3 ± 0.7	6.6
	241.	0.7 ± 0.4	4.5

Table 1: Brightness and Planck Brightness Temperature of the Diffuse Infrared Sky

shell temperature the helium would have lasted longer except for the FIRAS mirror transport mechanism (MTM) "hits", caused when trapped particles reset the position counters leading to the mirror carriage being driven into mechanical stops.

Even now, almost three years after the helium was depleted, the interior of the dewar is at about 55 K. Thus the InSb 1-5 μm detectors in the DIRBE are still working with good sensitivity.

The sky brightness measured by the DIRBE experiment on *COBE* at the South Ecliptic Pole[3] is given below in Table 1. By converting these sky brightnesses into brightness temperatures we can see the degree of telescope cooling required to achieve natural background limited performance in the infrared.

It is clear from the dewar outer shell temperature that space missions designed to study the 3.5 μm minimum in the zodiacal background can easily use radiatively cooled optics.

4. Detector Behavior

The experiments on *COBE* carry five kinds of detectors. At the lowest frequencies solid-state mixer diodes are used in the DMR experiment. Next up in frequency are the bolometers used in the FIRAS experiment and the two longest wavelength DIRBE channels. The third detector type is gallium-doped germanium extrinsic photoconductors (Ge:Ga) used in DIRBE at 60 and 100 μm. Arsenic-doped silicon (Si:As) blocked impurity band detectors are used in DIRBE at 12 and 25 μm, while photovoltaic indium antimonide (InSb) detectors are used from 1.25 to 4.9 μm.

The DMR detectors have shown no sensitivity to charged particles trapped in the Van Allen belts, while both the FIRAS and DIRBE detectors are excellent charged particle detectors. As a result, only the DMR can take data during passes through the South Atlantic Anomaly where the charged particle rate is highest. The data analysis task for FIRAS and DIRBE is complicated by the requirement that "glitches"

due to charged particles have to be found and removed before the data can be averaged, but this process can be automated to a very great extent by using trimmed means such as the mid-average instead of an arithmetic mean when adding data together. While deglitching is time consuming, the physical processes involved are well understood. A charged particle deposits much more energy in the detector than an infrared photon does, and it produces a very big impulsive signal. A much more serious problem involves hysteresis and long-term gain drifts associated with large doses of charged particles and passage over bright sources. The DIRBE detectors were annealed and recalibrated using an internal reference source after each passage through the SAA, and recalibrated after passage through the horns of the Van Allen belts. In addition, the DIRBE detectors look at a signal chopped at 32 Hz. Even so, the Ge:Ga detectors show a substantial hysteresis associated with galactic plane passages. The Si:As detectors show a small hysteresis, while the bolometers and InSb detectors do not.

5. FIRAS

The Far InfraRed Absolute Spectrophotometer instrument on *COBE* is a Martin-Puplett[2] or polarizing Michelson interferometer. The optical layout has dual inputs and outputs, and is very symmetrical. If I call the two inputs SKY and ICAL, then the two outputs, which are denoted LEFT and RIGHT, are given symbolically as

$$\text{LEFT} = \text{SKY} - \text{ICAL} \tag{1}$$

$$\text{RIGHT} = \text{ICAL} - \text{SKY} \tag{2}$$

The ICAL input is connected to an internal calibration source (the ICAL) that is quite close to a blackbody, so if the SKY input is a blackbody and the temperature of the ICAL is adjusted to match the temperature of the sky, the output signals are very small. This differential approach gives the FIRAS its incredible sensitivity to small deviations from a blackbody spectrum.

The FIRAS detectors are large composite bolometers that sense the output power by absorbing the radiation, converting this power into heat, and then detecting the temperature rise of a substrate using a very small and sensitive silicon resistance thermometer. The specific heat of the bolometer is minimized, which maximizes the temperature rise for a given input power, by making the substrate from the material with the highest known Debye temperature: diamond. Diamond is quite transparent to millimeter waves, however, so an absorbing layer is needed. Traditionally a layer of bismuth has been used as the absorber on composite bolometers, but the FIRAS detectors use a very thin layer of gold alloyed with chromium. The absorbing layer needs to have a surface impedance about one-half of the 377 Ohms/□ impedance of free space in order to absorb efficiently. This surface impedance can be obtained with a much thinner layer of gold than bismuth because gold is a good electrical conductor instead of a poor conductor like bismuth. This also serves to minimize the specific heat of the detector. The diameter of the octagonal diamond substrate is quite large: about 8 mm, which allows FIRAS to detect waves as long as 1 cm. A Winston cone, or compound parabolic concentrator, focuses a full π steradians onto the detectors. As a result the FIRAS instrument has a large étendue: 1.5 cm^2 sr.

The spectral data from FIRAS are obtained in the form of interferograms. The LEFT output is

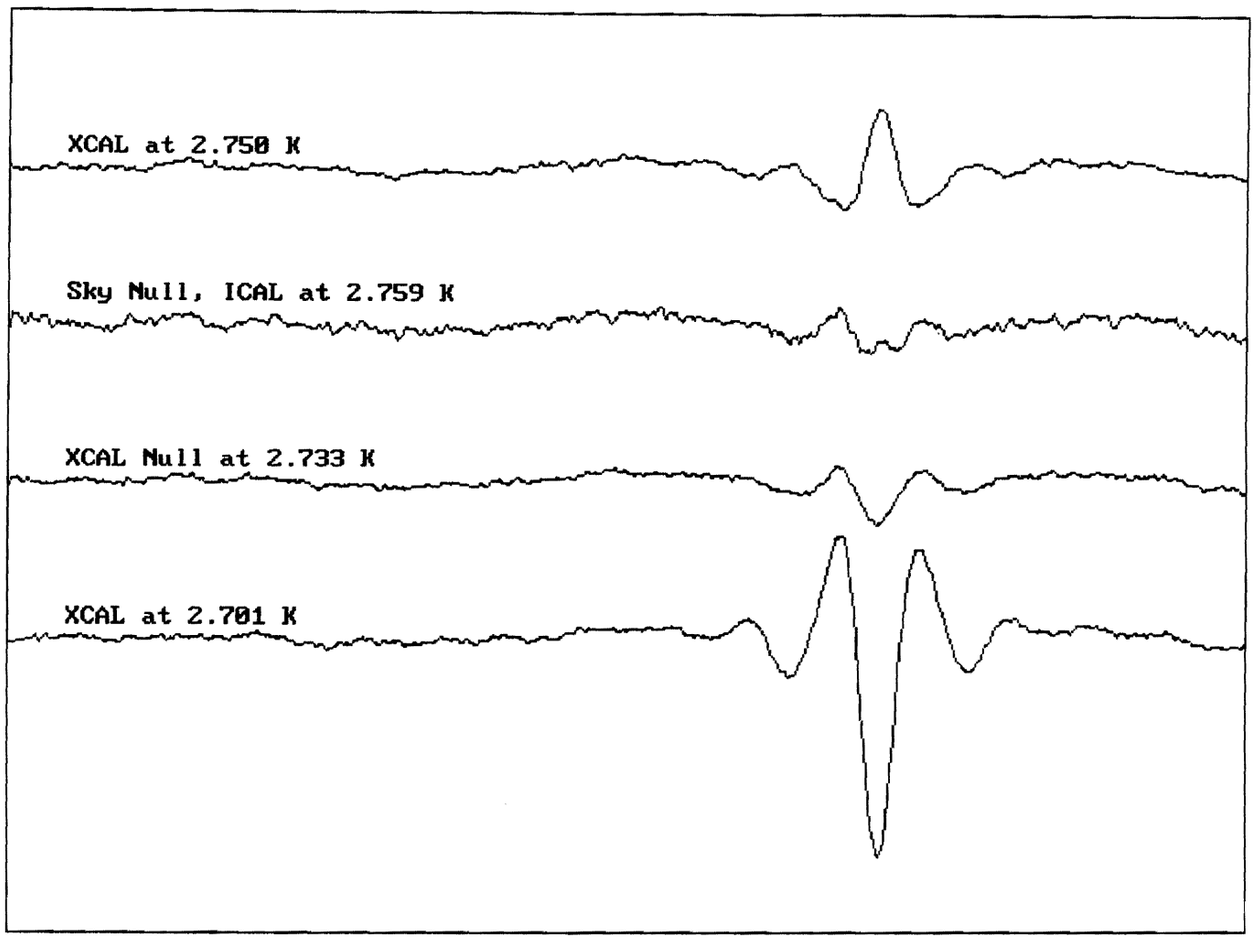

Fig. 1.— FIRAS interferograms from the Left Low channel looking at the sky and at the XCAL with T_X = 2.701, 2.733 and 2.750 K. The ICAL is fixed at 2.76 K

approximately

$$I_L(x) = \int_0^\infty \cos(2\pi\nu x) G(\nu) \left(I_\nu + \sum_i \epsilon_i(\nu) B_\nu(T_i) + U_\nu \right) d\nu \tag{3}$$

where the index i above runs over all the components in the FIRAS that had thermometers to measure T_i. These include the ICAL, the reference horn that connects to the ICAL, the sky horn, the bolometer housing, the optical structure of the FIRAS, and the dihedral mirrors that move to provide the variation in path length difference x. The ϵ_i's are the effective emissivities of the various components. The ICAL itself has $\epsilon \approx -0.97$, while the sky and reference horns have ϵ's of $\pm$ a few percent. The offset term U_ν was observed during flight to be approximately $10^{-5} \exp(-t/\tau) B_\nu(T_U)$ with a time constant τ of two months and a temperature $T_U \approx 15$ K. The SKY input I_ν can be either the sky or the external calibrator (XCAL). The XCAL is a movable re-entrant absorber that can be inserted at the top of the sky horn. The combination of sky horn plus XCAL forms a cavity with an absorptivity > 0.9999. With the XCAL inserted during periodic calibration runs, the SKY input is known to be $B_\nu(T_X)$. By varying T_X and the other T_i's, the calibration coefficients have been determined. See Fixsen *et al.*[4] for a more complete

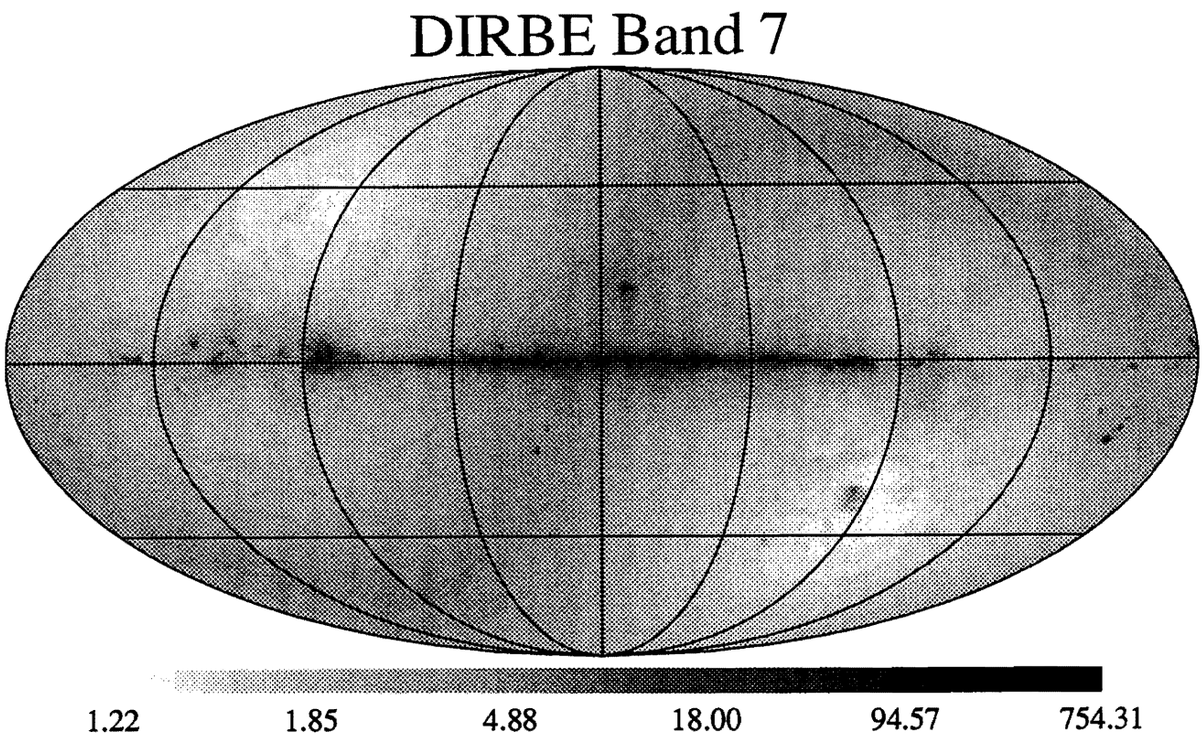

Fig. 2.— DIRBE Map at 60 μm in arbitrary units. The projection is in galactic coordinates with the galactic center in the center.

description of the calibration procedure. Figure 1 shows the interferograms used to determine the initial FIRAS measurement of the CMB spectrum[5] which agreed with a blackbody to better than 1%, while the latest FIRAS results[6] agree with a blackbody to better than 0.03% of the peak.

6. DIRBE

The DIRBE instrument has surveyed the entire sky over the wavelength range from 1.2 to 240 μm (in 10 bands) with an 0.7° beam[3]. The interplanetary dust emission is very strong in the 12-100 μm wavelength range. Figure 2 shows an image at 60 μm from the average of all the observations taken over the 10 months of cryogenic operation. The galactic plane is the brightest region of the sky, but the arch of the ecliptic plane can clearly be seen at high galactic latitudes. The darkest regions of the sky are near the ecliptic poles in this band, and a good model of the interplanetary dust cloud must be derived from the DIRBE data before any sensitive limits on extragalactic flux can be obtained.

The zodiacal dust cloud is faintest at 3.5 μm and 240 μm in the DIRBE data. Figure 3 shows the sky at 3.5 μm. The speckled appearance of the sky at high galactic latitudes is due to stars. The stars visible on this figure can identified with bright red giants and supergiants, such as α Sco and α Ori.

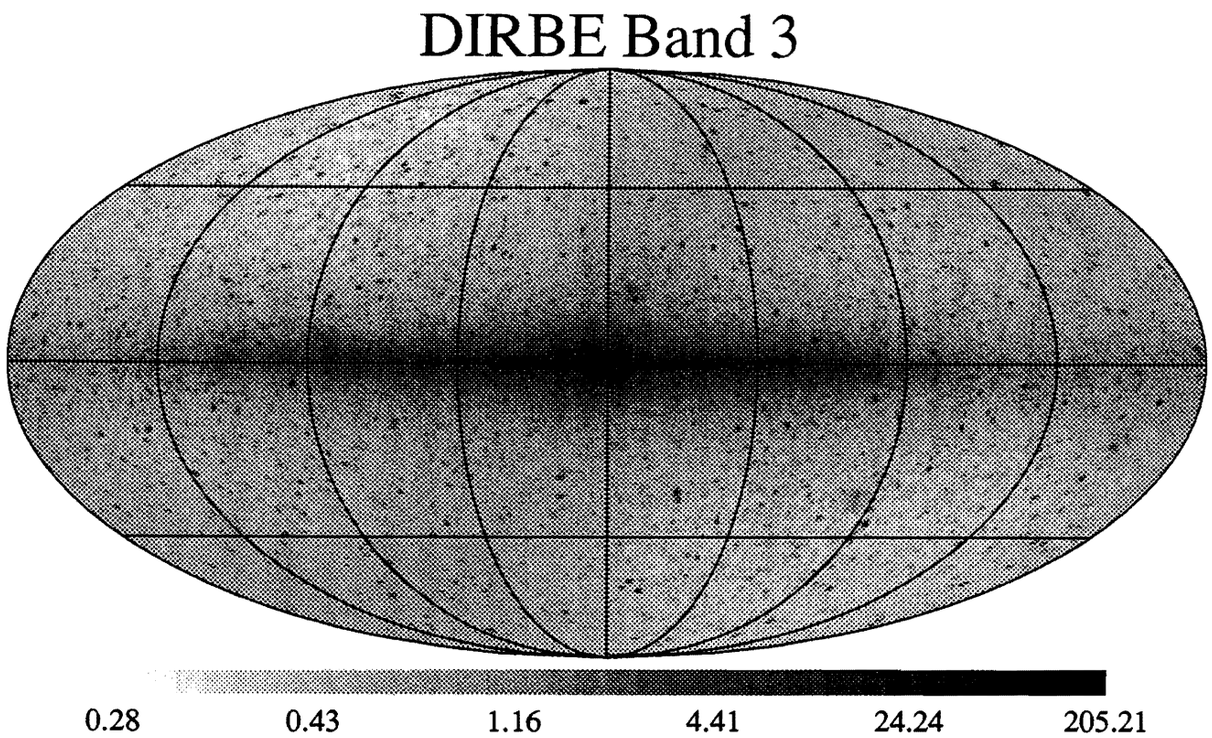

Fig. 3.— DIRBE Map at 3.5 μm in arbitrary units.

These stars can be seen in single sweeps of the DIRBE instrument and have been used to provide accurate attitude reconstruction. About 1 reliable star sighting per minute can be obtained, and by using the gyroscopes to propagate the attitude from star sighting to star sighting over an interval of about 20 minutes, a reconstructed attitude with an accuracy of about 1 arc minute is obtained, even though the beam size of the DIRBE is 42 arc minutes and it was not designed to serve as a star tracker[7].

At the longest DIRBE wavelength of 240 μm, shown in Figure 4, the high galactic latitude sky is dominated by the infrared "cirrus" discovered by the *IRAS* satellite. I feel that no simple geometrical model of the cirrus clouds will ever be sufficiently convincing to allow an extrapolation to "zero" galaxy. The $\csc|b|$ model for a plane-parallel galaxy is clearly inaccurate. This DIRBE map has been used as $G(l,b)$[8] in the FIRAS data analysis to derive a mean galactic spectrum, which then allowed very tight limits on deviations from a blackbody to be set[6]. But because of the lack of a geometrical model, an extragalactic flux with the same spectrum as the high latitude galactic emission will be assigned to the Milky Way.

7. DMR

The DMR instrument on *COBE* is designed to measure small temperature differences from place to place on the sky. The DMR consist of three separate boxes that are located just outside the dewar, one

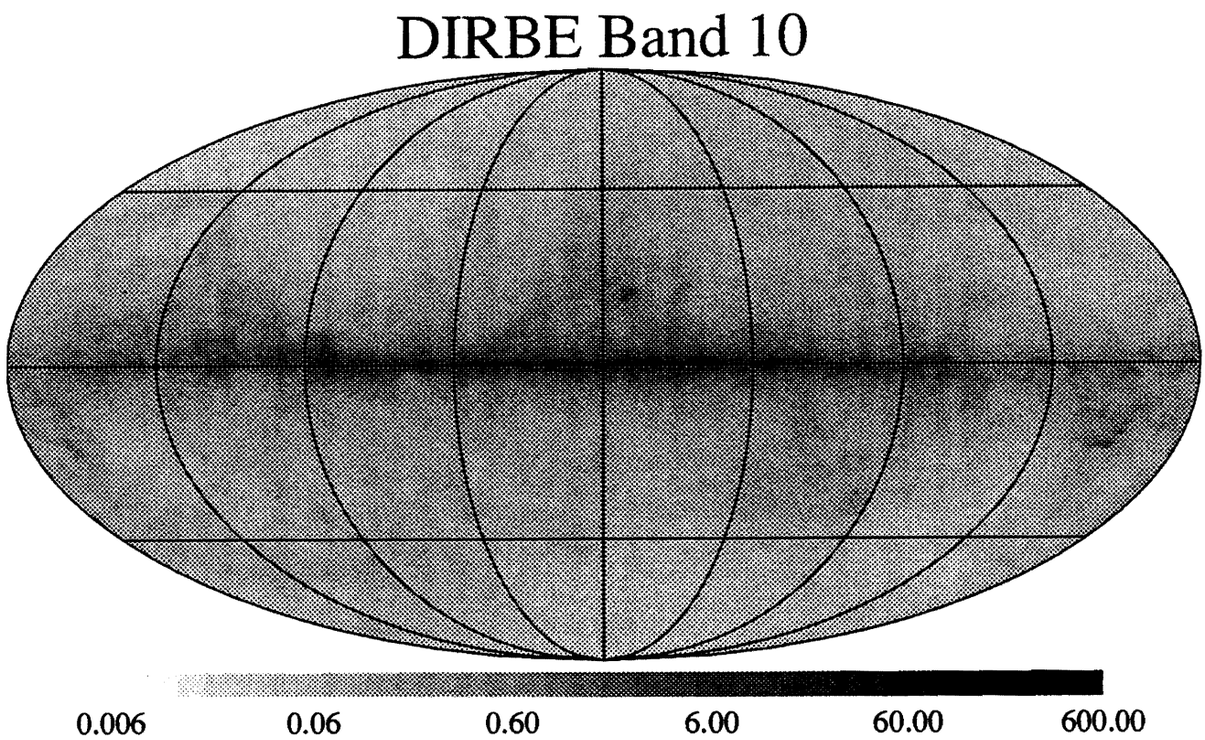

Fig. 4.— DIRBE Map at 240 μm in arbitrary units.

for each of the three frequencies of 31.5, 53 and 90 GHz. There are two largely independent receivers at each frequency. The field of view of each unit consists of two beams that are separated by a 60° angle that is bisected by the spin axis of the satellite. Each beam has a 7° FWHM. The DMR is only sensitive to the brightness difference between these two beams. This differencing is performed by a ferrite waveguide switch that connects the receiver input to one horn and then the other at a rate of 100 cycles per second. The signal then goes through a mixer, an IF amplifier and a video detector. The output of the video detector is demodulated by a lock-in amplifier synchronized to the input switch. The difference signal that results is recorded every 0.5 seconds for telemetry to the ground.

The sensitivity of the DMR varies between 15 and 40 mK in 1 second, depending on the channel. During the incubation period for *COBE* the signal predicted by credible cosmological theories fell dramatically, from $\Delta T/T$ equal to 1%[9] to 5-10 parts per million[10]. While this led to some concern about *COBE*'s ability to detect a signal, it also kept the DMR from being "scooped" by the balloon-borne competition[11], which presented an upper limit only $\sqrt{2}$ times higher than the ultimate *COBE* detection.

8. Summary

So far *COBE* has been a remarkably successful space experiment with dramatic observational consequences for cosmology. At least one new dramatic result from the DIRBE search for a cosmic

infrared background can be anticipated. In this search the DIRBE faces the difficulty that the CIB is expected to be many times fainter than the local infrared foregrounds from the Solar System and the Milky Way.

The most serious on-orbit problems experienced by *COBE* are gyro failures and the FIRAS MTM "hits". Gyro failures are unfortunately quite common, so the *COBE* spacecraft was designed with redundant gyros and autonomous fail-safe operation in mind. A sudden gyro failure four days after launch put this design to the test and it worked.

The FIRAS MTM hits were caused by trapped charged particles in the Van Allen belts resetting the position counter in the mirror transport mechanism. The mirror carriage can then collide with a mechanical stop, producing a large power dissipation inside the dewar. The reset pulse is carried out of the dewar by an optical fiber, and charged particles hitting the optical photodiode used to sense the reset pulse can cause the problem. When originally designed, charged particle events were considered and found to be unimportant. Later, the optical fibers were lossier than specified, but the signal was still much greater than the noise, and the charged particles event problem was not re-examined. During ground test, occasional transport lockups were seen, but their cause was a mystery. Because of these events an automatic resetter known as the "MTM Watchdog" or MDOG was added to the design. This circuit worked well in flight, and saved the FIRAS.

The FIRAS MTM was the only cryogenic mechanism that created problems during flight, but every single mechanism inside the dewar caused trouble during the pre-launch tests. The tuning fork chopper in DIRBE used stainless steel tines, and the ratio of mechanical dissipation to thermal conduction was high enough to cause the chopper to self heat to 15 K. Copper wires were added to the chopper tines to improve the cooling. The shutter in the DIRBE used to view the internal reference source would not operate under 1g until both the primary and backup drive coils were driven simultaneously. The springiness of the cables connected to the FIRAS XCAL was high enough at cryogenic temperatures to cause the calibrator to back out of the sky horn. This was discovered late in the testing because gravity had held the XCAL in the horn for all the earlier tests which were done in a vertical orientation.

As for lessons to be drawn from the *COBE* experience, I would try very hard to avoid moving parts inside dewars. If the thermal-vacuum chamber were to live up to its name of "Space Environment Simulator" it would include charged particle fluxes appropriate for the chosen orbit, and zero gravity. Since even the best simulator is still not as good as the real thing, what we really need is frequent, reliable and inexpensive access to space. This would give large numbers of scientists and engineers practical experience about what works and what doesn't in the space environment.

9. Acknowledgements

The National Aeronautics and Space Administration/Goddard Space Flight Center (NASA/GSFC) is responsible for the design, development, and operation of the Cosmic Background Explorer (COBE). Scientific guidance is provided by the COBE Science Working Group. GSFC is also responsible for the development of the analysis software and for the production of the mission data sets.

10. References

1. Bennett. C. L. *et al.* COBE Preprint 92-08. "Recent Results from COBE". to be published in The Third Teton Summer School: The Evolution of Galaxies and Their Environment. eds. H. A Thronson & J. M. Shull. 1992.

2. Martin. D. H. & Puplett. E. "Polarised Interferometric Spectrometry for the mm and Sub-mm Spectrum". *Infrared Physics* Vol. 10. pp. 105-109 1970.

3. Hauser. M. G.. Kelsall. T.. Moseley. S. H. Jr.. Silverberg. R. F.. Murdock. T.. Toller. G.. Spiesman. W. & Weiland. J.. 1991. "The Diffuse IR Background: COBE and other Observations". in the proceedings of the "After the First Three Minutes" Conference. Univ. of Md.. eds. S. S. Holt. C. L. Bennett. and V. Trimble. AIP Conference Proceeding 222. (American Institute of Physics: New York). pp 161-178.

4. Fixsen D. J.. *et al.* COBE Preprint 93-04. "Calibration of the Far Infrared Absolute Spectrophotometer (FIRAS) on the Cosmic Background Explorer (COBE)". submitted to *The Astrophysical Journal.* 1993.

5. Mather. J. C.. *et al.*. "A Preliminary Measurement of the Cosmic Microwave Background Spectrum by the Cosmic Background Explorer (COBE) Satellite". *The Astrophysical Journal (Letters).* Vol. 354. pp. L37-L41. 1990.

6. Mather *et al.* COBE Preprint 93-01. "The COBE FIRAS Measurement of the Cosmic Microwave Background Spectrum". submitted to *The Astrophysical Journal.* 1993.

7. Wright. E. L.. Kumar. V. K.. Freedman. I.. Rae. E.. Basappa. S.. Venkataraman. R. & Patt. F. S.. "COBE Attitude Refinement", in After The First Three Minutes. Proceedings of the Cosmology Workshop held at the University of Maryland 15-17 October 1990. eds. S.S. Holt. C.L. Bennett. and V. Trimble. AIP Conference Proceedings 222. American Institute of Physics. New York. pp. 179-182. 1991.

8. Wright. E. L.. *et al.*. "Preliminary Spectral Observations of the Galaxy with a 7° Beam by the Cosmic Background Explorer (COBE)". *The Astrophysical Journal.* Vol. 381. pp. 200-209. 1991.

9. Sachs. R. K. & Wolfe. A. M.. "Perturbations of a Cosmological Model and Angular Variations of the Microwave Background". *The Astrophysical Journal.* Vol. 147. p. 73. 1967.

10. Peebles. P. J. E.. "Large-Scale Background Temperature and Mass Fluctuations Due to Scale-Invariant Primeval Perturbations". *The Astrophysical Journal (Letters).* Vol. 263. pp. L1-L5. 1982.

11. Meyer. S. S.. Cheng. E. S. & Page. L. A.. "A Measurement of the Large-Scale CMB dT at 1.8 mm". *The Astrophysical Journal (Letters).* Vol. 371. pp. L7-L10. 1991.