THE COSMIC INFRARED BACKGROUND

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ABSTRACT

Cosmic infrared background radiation, expected to carry the radiative record of luminous objects since they first formed, has yet to be detected. The Diffuse Infrared Background Experiment (DIRBE) on the Cosmic Background Explorer (*COBE*) satellite is designed to search for this primeval background over the spectral range from 1 to 300 μm. Initial examination of data from this experiment show that foreground radiations from the solar system and Galaxy dominate the diffuse infrared sky brightness, with relative minima near 3.5 μm and in the submillimeter wavelength range. DIRBE measurements do not confirm some previous data from rockets and *IRAS*. Preliminary upper limits on the cosmic infrared background are generally above theoretical expectations for pregalactic and protogalactic sources, and substantially above estimated lower limits based upon observations of external galaxies. Careful foreground modeling is required to reduce these limits or identify an isotropic residual.

1. INTRODUCTION

The search for cosmic infrared background radiation (CIBR) is a relatively new field of observational cosmology. Measurement of this distinct radiative background, expected to arise from the cumulative emissions of pregalactic, protogalactic, and galactic systems, would provide new insight into the cosmic 'dark ages' following the decoupling of matter from the cosmic microwave background radiation (see, for example, early papers by Partridge and Peebles 1967; Low and Tucker 1968; Peebles 1969; Harwit 1970; Kaufman 1976; and more recent discussions by Bond, Carr, and Hogan 1986, 1991). Observationally, there have been no corroborated detections of the CIBR, though possible evidence for an isotropic infrared background in data from recent rocket experiments has been reported (Matsumoto et al. 1988a; Matsumoto 1990; Noda et al. 1991). The Diffuse Infrared Background Experiment (DIRBE) on the *COBE* spacecraft is the first satellite instrument designed specifically to carry out a systematic search for the CIBR. In this talk, largely extracted from the paper of Hauser et al. (1991), I report the current status of the DIRBE investigation, which is still in its data collection and early data reduction phase, and comment on a comparison of DIRBE measurements with those from instruments on sounding rockets and *IRAS*. Current conservative upper limits on the CIBR are compared with representative theoretical predictions and observational lower limits.

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2. MEASURING THE ABSOLUTE BRIGHTNESS OF THE INFRARED SKY

Observing the CIBR is a formidable task. Even when measurements are made from space with cryogenically cooled instruments, the local astrophysical foregrounds from interplanetary dust and the Galaxy strongly constrain our ability to measure and discriminate an extragalactic infrared background. Furthermore, since the absolute brightness of the CIBR is of paramount interest for cosmology, such measurements must be done relative to a well-established absolute flux reference, with instruments which strongly exclude or permit discrimination of all stray sources of radiation or offset signals which could mimic a cosmic signal.

Table 1 lists recent experiments capable of making absolute sky brightness measurements in the infrared. Two entries are given for the DIRBE instrument on *COBE*: one for the period of operation with liquid helium in the dewar, when measurements were made over the 1 - 300 μm spectral range, and one for the period following helium depletion, when the 1 - 4.5 μm sensors continued to operate. Table 1

Table 1. ABSOLUTE INFRARED BACKGROUND MEASUREMENTS

REFERENCE	λ(μm)	BEAM SIZE(°)	SKY COV	SOLAR ELONG	DATES
Murdock & Price 1985	2-30	0.1x0.25	40°-80° rad cone l=155°,b=-23°	$(\lambda-\lambda_\odot)$= 22°-180°	8/18/80; 7/31/81
Matsumoto et al. 1988a	0.7-5	4	32° rad cone l=150°,b=55°	$(\lambda-\lambda_\odot)$= 113°-180°	1/13/84
Noda et al. 1991	1.37-2.63	0.2x0.2	β=9°-50° λ=155° b~60° scan	130°-170°	2/22/90
Matsumoto et al. 1988b	100-300	7.6	15° rad cone l=203°,b=35°	140°-170°	2/22/87
IRAS (ZOHF, vers. 3)	12-100	0.5x0.5	All	80°-100° 60°-120°	1/26/83-11/22/83
COBE/DIRBE	1-300 1-3.4 pol.	0.7x0.7	All	64°-124°	11/18/89-9/21/90
COBE/DIRBE	1-4.5 1-3.4 pol.	0.7x0.7	All	64°-124°	9/21/90-present
COBE/FIRAS (high freq.)	100-500	7	All	94°	11/18/89-9/21/90

also lists the high frequency channel (100 to 500 μm) of the *COBE* Far Infrared Absolute Spectrophotometer (FIRAS) experiment. Though results are not yet available from these data, the FIRAS, with its all-sky coverage, excellent stray light rejection, absolute calibration, and high sensitivity, promises to be an important instrument for CIBR studies. Quantitative comparison of the measurements from the experiments listed in Table 1 is discussed below.

3. THE *COBE* DIFFUSE INFRARED BACKGROUND EXPERIMENT

The primary aim of the DIRBE is to conduct a definitive search for an isotropic CIBR, within the constraints imposed by the local astrophysical foregrounds. The experimental approach is to obtain absolute brightness maps of the full sky in 10 photometric bands (J[1.2], K[2.3], L[3.4], and M[4.9]; the four *IRAS* bands at 12, 25, 60, and 100 μm; and 120-200 and 200-300 μm bands). In order to facilitate discrimination of the bright foreground contribution from interplanetary dust, linear polarization is also measured in the J, K, and L bands, and all celestial directions are observed hundreds of times at all accessible solar elongation angles (depending upon ecliptic latitude) in the range 64° to 124°. The instrument is designed to achieve a sensitivity for each field of view of $\lambda I_{\lambda} = 10^{-13}$ W cm^{-2} sr^{-1} (1 σ, 1 year). For further general information about the *COBE* mission, see the descriptions by Mather (1982) and Gulkis et al. (1990). Early scientific results from the mission were summarized by Mather et al. (1990).

The DIRBE instrument is an absolute radiometer, utilizing an off-axis folded Gregorian telescope with a 19-cm diameter primary mirror. The optical configuration (Magner 1987) is carefully designed for strong rejection of stray light from the Sun, Earth limb, Moon or other off-axis celestial radiation, or parts of the *COBE* payload (Evans, 1983). The instrument, which is maintained at a temperature below 2 K within a superfluid helium dewar, measures absolute brightness by chopping between the sky signal and a zero-flux internal reference at 32 Hz. Instrumental offsets are measured by closing a cold shutter located at the prime focus. A radiative offset signal in the long wavelength detectors arising from JFETs (operating at about 70 K) used to amplify the detector signals was identified and measured in this fashion. All spectral bands view the same instantaneous field-of-view, 0.7° x 0.7°, oriented at 30° from the dewar central axis, about which the *COBE* spacecraft spins at 0.8 rpm. This allows the DIRBE to modulate solar elongation angles by 60° during each rotation, and to sample fully 50% of the celestial sphere each day. Radiative reference sources are used to stimulate all detectors when the shutter is closed to monitor the stability and linearity of the instrument response. The highly redundant sky sampling and frequent response checks provide precise photometric closure over the sky for the duration of the mission. Calibration of the photometric scale is obtained from observations of isolated bright celestial sources.

Routine surveying of the sky was carried out from December 11, 1989 until depletion of the liquid helium on September 21, 1990. The interior of the dewar has subsequently warmed to about 50 K. Though the detectors at wavelengths longer than 5 μm no longer provide useful data, the J, K, L, and M band InSb detectors continue to provide usable data at about 20% of the original sensitivity. The present plan is to operate the DIRBE through a second year. This will allow completion of sky mapping over one full orbit around the Sun to aid modeling of the interplanetary dust foreground, and will enable a search for temporal variation in this foreground during the second year.

The DIRBE sky maps show the dominant anticipated features of galactic starlight and zodiacal light at short wavelengths, and emission from the interplanetary and interstellar media at long wavelengths. A composite of the 1.2, 2.3, and 3.4 μm images was presented by Mather et al. (1990). Because extinction at these wavelengths is far less than in visible light, the disk and bulge stellar populations of the Milky Way are dramatically apparent in this image. The patchy infrared cirrus noted in *IRAS* data (Low et al. 1984) is evident at all wavelengths longer than 25 μm. The DIRBE data will clearly be a valuable new resource for studies of the interplanetary medium and Galaxy as well as the search for the CIBR.

4. COMPARISON OF INFRARED SKY BRIGHTNESS MEASUREMENTS

Hauser et al. (1991) compared the preliminary DIRBE sky brightness measurements with those from the earlier experiments listed in Table 1, selecting DIRBE data at the same time of year as well as celestial direction so as to minimize differences in the foreground from interplanetary dust. There are some discrepancies of note: DIRBE data show a steeper slope in the north galactic polar spectrum from 1.2 to 3.4 μm than that reported by Matsumoto et al. (1988a), and fainter 60 and 100 μm sky brightnesses toward the ecliptic poles than that found by *IRAS* (at 100 μm the difference is about a factor of 2.6). Since a steeper 1.2 to 3.4 μm energy distribution is more consistent with the expected contributions from starlight and zodiacal light than the data of Matsumoto et al., these DIRBE data raise some doubt about their inference of an extragalactic component near 2.2 μm. The differences between the DIRBE and *IRAS* results suggest errors in the low-frequency gain and zero point determinations for the *IRAS* instrument. Further comparisons with *IRAS* data are in progress. Comparison of the DIRBE measurements acquired at the same time of year and in the same celestial direction as those recently reported by Noda et al. (1991) awaits further reduction of the DIRBE data.

5. CURRENT LIMITS ON THE COSMIC INFRARED BACKGROUND RADIATION

The sky brightness over the infrared spectral range is dominated by solar system and galactic sources. Until the various sources are properly discriminated and subtracted, the most credible limits on the CIBR are the observed brightnesses in a relatively dark direction, such as the ecliptic poles. A preliminary DIRBE spectrum toward the south ecliptic pole (Mather et al. (1990); see also Hauser et al. (1991), Table 2) shows that the faintest levels of the foreground emissions occur at 3.4 μm (λI_λ = 15±6 pW cm^{-2} sr^{-1}) and near 240 μm (λI_λ = 7±4 pW cm^{-2} sr^{-1}), confirming these as the most sensitive spectral windows for the CIBR search. The sensitivity of the *COBE* DIRBE and FIRAS measurements in each of their respective fields-of-view is generally well below the observed sky brightness toward the ecliptic pole (Hauser et al. 1991). With the *COBE* data in hand, discrimination of foreground emission, rather than measurement sensitivity, is clearly the major challenge in searching for the CIBR.

There have been reports of upper limits on, or possible detections of, isotropic residuals in the infrared sky brightness from previous rocket experiments (Matsumoto et al. (1988a); Matsumoto (1990)). These investigators have arrived at these limits after attempting to discriminate the various foreground components of emission contributing to their measurements. Because of limited sky coverage and brief time to check possible systematic measurement errors, results from the rocket experiments require confirmation.

To put the observational data into a cosmological context, Hauser et al. (1991) compared estimated contributions to the CIBR from pregalactic and protogalactic sources in a dust-free universe (Bond, *Carr, and Hogan 1986*). The present conservative observational limits are beginning to constrain some of the theoretical models (see also Carr et al. (1991)). However, in a dusty universe energy from short wavelength luminous sources can be redistributed into the far infrared, introducing much uncertainty into predictions of the CIBR spectral energy distribution. Strong observational constraints will have to be established throughout the infrared spectrum to constrain the many possible scenarios.

Recent progress has been made on determining lower limits to the extragalactic infrared background. For example, Cowie et al. (1990) have estimated the integrated contribution of galaxies at 2.2 μm to be λI_λ = 0.5 pW cm^{-2} sr^{-1} on the basis of deep galaxy counts. Hacking and Soifer (1991) have used galaxy luminosity functions derived from *IRAS* data to predict minimum diffuse backgrounds (integrated to z=3) at 25, 60, and 100 μm of 0.1, 0.2, and 0.4 pW cm^{-2} sr^{-1} respectively. Beichman and Helou (1991) have used synthesized galaxy spectra, also based largely on *IRAS* data, to estimate the diffuse infrared background due to galaxies. At 300 μm, their minimum estimated brightness (integrated to z=3) is 0.2 pW cm^{-2} sr^{-1}. The integrated galaxy far-infared background contribution may exceed these estimates substantially if there has been evolution in galaxy luminosity or space density: deeper counts from future space infrared observatories such as ISO and SIRTF will improve these estimates. Even these minimum extragalactic background contributions should be detectable if the foreground contributions to the *COBE* measurements can be modeled to about the 1% level.

6. CONCLUSION

Measurement of the cosmic infrared background radiation will enhance our understanding of the epoch between decoupling and galaxy formation. The high quality and extensive new measurements of the absolute infrared sky brightness obtained with the DIRBE and FIRAS experiments on the *COBE* mission promise to allow a definitive search for this elusive background, limited primarily by the difficulty of distinguishing it from bright astrophysical foregrounds. The spectral decade from about 6 to 60 µm will have relatively weak limits until measurements are made from outside the interplanetary dust cloud.

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