A TENTATIVE DETECTION OF THE COSMIC INFRARED BACKGROUND AT 3.5 \( \mu m \)
FROM COBE/DIRBE OBSERVATIONS

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ABSTRACT

Foreground emission and scattered light from interplanetary dust (IPD) particles and emission from Galactic stellar sources are the greatest obstacles to determining the cosmic infrared background (CIB) from diffuse sky measurements in the \( \sim 1-5 \) \( \mu m \) range. We use ground-based observational limits on the K-band intensity of the CIB in conjunction with sky maps obtained by the Diffuse Infrared Background Experiment (DIRBE) on the Cosmic Background Explorer (COBE) satellite to reexamine the limits on the CIB at 1.25, 3.5, and 4.9 \( \mu m \). Adopting a CIB intensity of 7.4 nW m\(^{-2}\) sr\(^{-1}\) at 2.2 \( \mu m \), and using the 2.2 \( \mu m \) DIRBE sky map from which the emission from the IPD cloud has been subtracted, we create a spatial template of the Galactic stellar contribution to the diffuse infrared sky. This template is then used to subtract the contribution of the diffuse Galactic stellar emission from the IPD emission–subtracted DIRBE sky maps at 1.25, 3.5, and 4.9 \( \mu m \). The DIRBE 100 \( \mu m \) data are used to estimate the small contribution of emission from interstellar dust at 3.5 and 4.9 \( \mu m \). Our method significantly reduces the errors associated with the subtraction of Galactic starlight, leaving only the IPD emission component as the primary obstacle to the detection of the CIB at these wavelengths. The analysis leads to a tentative detection of the CIB at 3.5 \( \mu m \) with an intensity of \( \nu I_\nu = [9.9 + 0.312 \lambda I_{\lambda \text{CIB}}(\lambda) - 7.4] \) \pm 2.9 nW m\(^{-2}\) sr\(^{-1}\), where \( \nu I_{\lambda \text{CIB}}(\lambda) \) is the CIB intensity at 2.2 \( \mu m \) in units of nW m\(^{-2}\) sr\(^{-1}\). The analysis also yields new upper limits (95% confidence limit) on the CIB at 1.25 and 4.9 \( \mu m \) of 68 and 36 nW m\(^{-2}\) sr\(^{-1}\), respectively. The cosmological implications of these results are discussed in this Letter.

Subject headings: cosmology: observations — diffuse radiation — infrared: general

1. INTRODUCTION

The determination of the cosmic infrared background (CIB) from diffuse sky measurements is greatly hampered by the presence of foreground emission and scattered light from the interplanetary dust (IPD) cloud, emission from discrete and unresolved stellar components in our Galaxy, and from dust in the interstellar medium (ISM). In a recent publication, Hauser et al. (1998) presented the results of the search for the CIB in the 1.25–240 \( \mu m \) wavelength region that was conducted with the Diffuse Infrared Background Experiment (DIRBE) on the Cosmic Background Explorer (COBE) satellite. Careful subtraction of foreground emission from the IPD cloud (Kelsall et al. 1998) and from stellar and interstellar Galactic emission components (Arendt et al. 1998) revealed a residual emission component in the DIRBE sky maps that, after detailed analysis of the random and systematic uncertainties, was consistent with a positive signal at 100, 140, and 240 \( \mu m \). Subsequent rigorous tests showed that only the 140 and 240 \( \mu m \) signals were isotropic, a strict requirement for their extragalactic origin. Only upper limits for the CIB intensity were given for \( \lambda = 1.25-60 \) \( \mu m \), where the CIB detection was hindered by residual emission from the IPD cloud. In the 1.25–4.9 \( \mu m \) wavelength region, uncertainties in the subtraction of the Galactic stellar component contributed to the uncertainties as well. The upper limits on the CIB determined by Hauser et al. (1998) can be found in Table 2 below.

In this Letter, we use a new empirical model for the Galactic stellar emission in order to reduce the uncertainties attributed by the DIRBE team to the removal of this component. Our analysis relies on the modeling and error analysis of the IPD and the ISM contributions to the diffuse emission presented by Kelsall et al. (1998) and Arendt et al. (1998). As a starting point in our analysis, we use the DIRBE 1.25, 2.2, 3.5, and 4.9 \( \mu m \) all-sky maps from which the emission from interplanetary (zodiacal) dust has been subtracted (Kelsall et al. 1998). The intensity, \( I_\lambda(\lambda) \), of these maps should, in principle, contain only the Galactic emission (starlight and ISM emission) and the CIB. Assuming that the CIB is somehow determined from different independent observations at wavelength \( \lambda_0 \), then subtraction of this background, \( I_{\lambda \text{CIB}}(\lambda) \), from the corresponding DIRBE sky map will create a spatial template of the Galactic emission at this wavelength. At \( \lambda_0 = 2.2 \) \( \mu m \), emission from the ISM is negligible, and this template corresponds to the Galactic starlight. Correlation of this stellar template map, \( S_\lambda(\lambda) \), with the IPD emission–subtracted sky maps should yield a straight line with a slope of \( S_\lambda(\lambda)/S_\lambda(\lambda_0) \), corresponding to the average Galactic stellar flux ratio, and a nonzero intercept at zero \( S_\lambda(\lambda_0) \) intensity, which one can identify as the CIB contribution to \( I_\lambda(\lambda) \) after a small correction for the ISM emission is subtracted at 3.5 and 4.9 \( \mu m \).

The method is based on the assumption that the difference map \( I_{\lambda}(\lambda_0) - I_{\lambda \text{CIB}}(\lambda_0) \) is a good representation of \( S_\lambda(\lambda_0) \), the intensity map of the Galactic stellar contribution at \( \lambda_0 \). Correlation of \( S_\lambda(\lambda) \) with maps at other wavelengths will allow the identification and removal of the stellar emission at those wavelengths. For \( I_{\lambda \text{CIB}}(\lambda_0) \), we use the recently determined ground-based K-band (\( \lambda = 2.2 \) \( \mu m \)) galaxy counts, which give a strict lower limit of 7.4 nW m\(^{-2}\) sr\(^{-1}\) to the CIB intensity at that wavelength (see, e.g., Gardner 1996). Plots of the K-band contribution to the CIB versus the magnitude (see, e.g., Pozzetti et al. 1998) show a decrease in the intensity at faint magnitudes, suggesting that the contribution of faint galaxies to the inte-
grated light is small. We therefore adopt the above intensity as the nominal value for the CIB at 2.2 μm and explicitly state the dependence of our results on this value.

We apply the method to regions in the DIRBE sky maps that were identified in the DIRBE analysis as high-quality (HQ) regions where errors in the subtractions of the foreground emission are expected to be small (Hauser et al. 1998; see also § 2.1). The results show an extremely good correlation between \( I_\nu(2.2 \text{ μm}) \) and \( S_\nu(\lambda_j) \) (\( \lambda_j = 1.25, 3.5, \text{ and } 4.9 \text{ μm} \)), characterized by a narrow dispersion and a positive intercept. Concentrating on HQB, the high-quality region emphasized in the analysis by the DIRBE team, we identify the uncertainties in the method as the difference between the intercept in HQBN and that in HQBS, the northern and southern sections of HQB, respectively. These uncertainties are small compared with those associated with the subtraction of the faint source model (FSM) that the DIRBE team had used to characterize the contribution of unresolved Galactic stellar sources (Arendt et al. 1998). At 1.25 and 4.9 μm, uncertainties in the residuals are about equally divided between the systematic errors in the subtraction of the zodiacal light and the subtraction of the FSM contributions to the emission. So a priori we do not expect our method to result in a significant reduction in the uncertainties in the CIB determination at these wavelengths. However, at 3.5 μm, uncertainties in the Hauser et al. (1998) results are dominated by systematic errors in the FSM, which are significantly larger than the errors in the proposed method. With this reduction of uncertainties, our analysis yields a positive detection of the CIB at 3.5 μm. The values derived for the CIB in different regions of the sky fall within the uncertainties, providing a simple test for their isotropic character.

2. ANALYSIS

2.1. An Empirical Model of Galactic Starlight

As described in § 1, we adopt a value of \( \nu I_\text{cm}(2.2 \text{ μm}) = 7.4 \text{ nW m}^{-2} \text{ sr}^{-1} \) for the CIB intensity in the K band and create a difference map \( S_\nu(2.2 \text{ μm}) = I_\nu(2.2 \text{ μm}) - I_\text{cm}(2.2 \text{ μm}) \), which we identify as the spatial template of the Galactic stellar contribution to the diffuse IR sky. We chose for our analysis high-quality (HQ) regions of the sky, identified as such for their location at high Galactic latitudes (b) and ecliptic latitudes (β), in which the contributions from the Galactic and zodiacal emission components are relatively small compared with other regions of the sky. HQA is a region encompassing 8780 deg² of the sky at |b| > 30°, |β| > 25°, including sections in both the northern and southern hemispheres. The HQB region is a smaller area of 854 deg² contained within HQA at |b| > 60°, |β| > 45°. Both HQ regions exclude several locations where the 100 μm ISM intensity is strong, \( I_{\text{ISM}} > 0.2 \text{ MJy sr}^{-1} \).

Figure 1 shows the correlation of \( I_\nu(\lambda_j) \) versus \( \nu S_\nu(2.2 \text{ μm}) \) within HQB for \( \lambda_j = 1.25, 3.5, \text{ and } 4.9 \text{ μm} \). A linear least-squares fit was performed to derive the intercepts and slopes of these correlations in addition to the correlation coefficients. Results of these fits for the HQA and HQB regions and their north and south subregions (e.g., HQAN and HQAS) are presented in Table 1. The slopes of the correlations in Figure 1 and Table 1 represent the colors of stellar emission. Most of this emission is unresolved (the brightest resolved sources lie outside the ranges displayed in Figure 1 and were excluded from the fit), but the colors are still a very good match to those of M and K giants, as shown in Figure 2 of Arendt et al. (1994). The intercepts of the correlations, \( I_{\text{tot}}(\lambda_j) \), give the remaining intensity of any emission unassociated with Galactic starlight. At 3.5 and 4.9 μm, this includes emission from the ISM. Following Arendt et al. (1998), we estimate and remove the mean level of this ISM emission by scaling the average intensity of the 100 μm ISM emission seen by DIRBE in these regions by factors of 0.00183 and 0.00292 at 3.5 and 4.9 μm, respectively. The resulting contribution of the ISM to the emission in each band is also listed in Table 1.

2.2. Uncertainties

Three sources of errors contribute to the uncertainties in the derived intensity of the CIB. The first consists of the uncertainties in the residuals of the zodiacal emission, \( \sigma_z \), contained in the DIRBE sky maps \( I_\nu(\lambda_j) \) (\( \lambda_j = 1.25, 3.5, \text{ and } 4.9 \text{ μm} \)) as well as the \( S_\nu(2.2 \text{ μm}) \) difference map. The second uncertainty is that associated with the subtraction of the emission from the ISM. The third results from the uncertainty in the value of the intercept, denoted hereafter as \( \sigma_{\text{res}} \). The total uncertainty in the residual emission is given by

\[
\sigma_{\text{res}}(\lambda_j) = (\sigma_z^2(\lambda_j) + \sigma^2_{\text{ISM}}(\lambda_j))^{1/2}
+ [S_\nu(\lambda_j)/S_\nu(2.2 \text{ μm})\sigma_z(2.2 \text{ μm})]^2 + \sigma^2_{\text{res}}(\lambda_j))^{1/2}
= [\sigma_z^2(\lambda_j) + \sigma^2_{\text{ISM}}(\lambda_j) + \sigma^2_{\text{ISMM}}(\lambda_j)]^{1/2},
\]

(1)

where \( \sigma^2_{\text{ISMM}}(\lambda_j) \equiv [S_\nu(\lambda_j)/S_\nu(2.2 \text{ μm})\sigma_z(2.2 \text{ μm})]^2 + \sigma^2_{\text{res}}(\lambda_j) \) is
the total uncertainty associated with our empirical stellar model. Table 2 lists the total uncertainty, \( \sigma_{\text{sm}}(\lambda_j) \), and the various contributions to the uncertainty in the value of \( I_{\text{res}}(\lambda_j) \). The values of \( \sigma_{\text{sm}}(\lambda_j) \) were taken from Arendt et al. (1998; Table 6), and the value of \( \sigma_{\text{sm}}(\lambda_j) \) was taken to be equal to the absolute value of the difference in the value of \( I_{\text{res}}(\lambda_j) \) between HQBN and HQBS. The systematic errors, \( \sigma_{\text{sm}}(\lambda_j) \) derived by Arendt et al. (1998; Table 6) that are due to uncertainties in the subtraction of the FSM are listed in the table also. A comparison of \( \sigma_{\text{sm}}(\lambda_j) \) with the error associated with the FSM illustrates the effectiveness of our method in reducing the uncertainties in removing the Galactic stellar emission component.

### 2.3. Residual Intensities

The residual intensity after subtraction of the IPD, stellar, and ISM foregrounds is given by \( I_{\text{res}} = I_{\text{int}} - I_{\text{ISM}} \). Following Hauser et al. (1998), we derive the analysis of the HQB region, which can be summarized as

\[
\nu I_{\text{res}}(\text{nW m}^{-2} \text{ sr}^{-1}) = 26.9 + 2.31 \Delta_{\text{CIB}}(2.2 \mu\text{m}) \pm 20.6 \text{ for } \lambda = 1.25 \mu\text{m},
\]

\[
= 9.9 + 0.312 \Delta_{\text{CIB}}(2.2 \mu\text{m}) \pm 2.9 \text{ for } \lambda = 3.5 \mu\text{m},
\]

\[
= 23.3 + 0.113 \Delta_{\text{CIB}}(2.2 \mu\text{m}) \pm 6.4 \text{ for } \lambda = 4.9 \mu\text{m},
\]

\( (2) \)

### Table 2

| Region | Wavelength (\( \mu\text{m} \)) | Number of Pixels | Correlation Coefficient | \( \nu J_{\text{res}}(\lambda_j) \) (nW m\(^{-2}\) sr\(^{-1}\)) | \( \nu J_{\text{res}}(\lambda_j) \) (nW m\(^{-2}\) sr\(^{-1}\)) |
|--------|-----------------|-----------------|------------------------|-----------------|-----------------|
| HQB... | 1.25            | 7460            | 0.95                   |                  |                  |
| HQBN...| 1.25            | 3643            | 0.95                   |                  |                  |
| HQBS...| 1.25            | 3817            | 0.95                   |                  |                  |
| HQA... | 1.25            | 37353           | 0.96                   |                  |                  |
| HQAS...| 1.25            | 36564           | 0.96                   |                  |                  |
| HQB... | 3.5             | 7461            | 0.98                   | 0.3123 \(\pm\) 0.0007 | 11.34 \(\pm\) 0.07 |
| HQBN...| 3.5             | 3643            | 0.98                   | 0.3112 \(\pm\) 0.0010 | 10.93 \(\pm\) 0.09 |
| HQBS...| 3.5             | 3818            | 0.98                   | 0.3111 \(\pm\) 0.0009 | 11.93 \(\pm\) 0.09 |
| HQA... | 3.5             | 73905           | 0.98                   | 0.3141 \(\pm\) 0.0002 | 11.95 \(\pm\) 0.03 |
| HQAN...| 3.5             | 37349           | 0.98                   | 0.3125 \(\pm\) 0.0003 | 11.69 \(\pm\) 0.04 |
| HQAS...| 3.5             | 36556           | 0.98                   | 0.3142 \(\pm\) 0.0003 | 12.36 \(\pm\) 0.04 |
| HQB... | 4.9             | 7461            | 0.88                   | 0.1133 \(\pm\) 0.0007 | 24.85 \(\pm\) 0.07 |
| HQBN...| 4.9             | 3643            | 0.91                   | 0.1116 \(\pm\) 0.0008 | 23.89 \(\pm\) 0.08 |
| HQBS...| 4.9             | 3818            | 0.88                   | 0.1101 \(\pm\) 0.0010 | 26.19 \(\pm\) 0.10 |
| HQA... | 4.9             | 73905           | 0.88                   | 0.0987 \(\pm\) 0.0004 | 28.31 \(\pm\) 0.05 |
| HQAN...| 4.9             | 37348           | 0.72                   | 0.1015 \(\pm\) 0.0005 | 26.96 \(\pm\) 0.06 |
| HQAS...| 4.9             | 36553           | 0.61                   | 0.0922 \(\pm\) 0.0006 | 30.10 \(\pm\) 0.07 |

* All values are given in units of nW m\(^{-2}\) sr\(^{-1}\).

where the quoted errors represent 1 \( \sigma \) uncertainties and \( \Delta_{\text{CIB}}(2.2 \mu\text{m}) \) \( = [I_{\text{CIB}}(2.2 \mu\text{m})] - 7.4 \) represents the difference in the actual value of the CIB at 2.2 \( \mu\text{m} \) (in units of nW m\(^{-2}\) sr\(^{-1}\)) and the nominal value adopted in our model. Values of \( \nu J_{\text{res}}(\nu) \) for \( \Delta_{\text{CIB}}(2.2 \mu\text{m}) = 0 \) are listed in Table 2. Only the 3.5 and 4.9 \( \mu\text{m} \) residuals are positive (>3 \( \sigma \)) and therefore potential detections of the CIB.

### 2.4. Isotropy Tests

We tested the residual intensities in the 3.5 and 4.9 \( \mu\text{m} \) bands for isotropy, an expected property of the CIB. Table 1 shows that the residual 3.5 \( \mu\text{m} \) emission is isotropic, as evident from the agreement between the mean intensities in the various HQ regions. However, a more detailed analysis shows the presence of a low-level large-scale gradient. This gradient is caused by residual emission from IPD particles. This gradient would have been undetected in the analysis of Hauser et al. (1998) using the FSM to subtract the Galactic stellar emission. The reduction in this gradient from the level found by Hauser et al. (1998) to its present level is the result of our more accurate subtraction of the stellar emission component. Without the existence of this weak gradient, the residual would qualify as a definite detection of the CIB. Instead, we conservatively regard this result as a tentative detection of the CIB at 3.5 \( \mu\text{m} \).

The same gradient seen in the 3.5 \( \mu\text{m} \) image is significantly stronger in the 4.9 \( \mu\text{m} \) residual map and is responsible for the larger dispersion in the mean intensities in the various HQ regions. We therefore consider the 4.9 \( \mu\text{m} \) result as only an upper limit.

### 3. DISCUSSION

Figure 2 shows the current limits on and tentative detection of the extragalactic background light (EBL) in the 0.1–10 \( \mu\text{m} \) wavelength region. The filled squares represent the detections at 0.36, 0.45, 0.67, and 0.81 \( \mu\text{m} \) from a background fluctuation analysis of the Hubble Deep Field (HDF) (Pozzetti et al. 1998). The total EBL intensity in the 0.36–3.5 \( \mu\text{m} \) wavelength region is 16 nW m\(^{-2}\) sr\(^{-1}\), about equal to the total integrated CIB intensity in the 140–1000 \( \mu\text{m} \) region (Hauser et al. 1998; Fixsen et al. 1998; Dwek et al. 1998).

Figure 2 compares several model predictions with the observational constraints. The solid line represents the model of
Fig. 2.—The UV determination of the EBL and our COBE/DIRBE limits and a tentative 3.5 μm detection (filled circles) are compared with select model predictions: Franceschini et al. (1997; solid line) and Malkan & Stecker (1998; dashed line). The dotted line represents model ED from Dwek et al. (1998) scaled up by a factor of 1.2. The filled squares represent HDF detections by Pozzetti et al. (1998), the filled triangle represents the 2.2 μm lower limit from galaxy counts (Gardner 1996), and the open circle is the DIRBE upper limit at 2.2 μm (Hauser et al. 1998).

Franceschini et al. (1997), and the dashed line represents that calculated by Malkan & Stecker (1998). Both models are consistent with the tentative 3.5 μm detection. However, they are incomplete with regard to their EBL prediction at shorter wavelengths. The dotted line represents two models calculated by Dwek et al. (1998) in which the UV and optically determined cosmic star formation rate presented by Madau, Pozzetti, & Dickinson (1998) was augmented either by hidden starbursts at z ≈ 1.5 (model ED) or by hidden starbursts at high redshifts (model RR). The models give similar results in the 0.1–10 μm wavelength regions and were scaled up by a factor of 1.2 in order to provide a better fit to the tentative 3.5 μm detection. However, the models produce an excess flux at 0.36 and 0.45 μm that requires some modifications in the model assumptions.

Most models to date have concentrated on predicting the EBL at mid- and far-IR wavelengths, and they appear to be incomplete in the UV and near-IR regions of the spectrum. Our tentative detection of the CIB at 3.5 μm adds an important new constraint on CIB models in this wavelength region.

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