AN EMPIRICAL DECOMPOSITION OF NEAR-INFRARED EMISSION INTO GALACTIC AND EXTRAGALACTIC COMPONENTS

RICHARD G. ARENDT and ELI DWEEK

NASA Goddard Space Flight Center, Code 685, Greenbelt, MD 20771; arendt@stars.gsfc.nasa.gov, edwek@stars.gsfc.nasa.gov
Received 2002 June 25; accepted 2002 November 6

ABSTRACT

We decompose the COBE/DIRBE observations of the near-IR sky brightness (minus zodiacal light) into Galactic stellar and interstellar medium (ISM) components and an extragalactic background. This empirical procedure allows us to estimate the 4.9 μm cosmic infrared background (CIB) as a function of the CIB intensity at shorter wavelengths. A weak indication of a rising CIB intensity at λ > 3.5 μm hints at interesting astrophysics in the CIB spectrum, or warns that the foreground zodiacal emission may be incompletely subtracted. Subtraction of only the stellar component from the zodiacal-light-subtracted all-sky map reveals the clearest 3.5 μm ISM emission map, which is found to be tightly correlated with the ISM emission at far-IR wavelengths.

Subject headings: diffuse radiation — dust, extinction — Galaxy: stellar content — infrared: galaxies — infrared: ISM — infrared: stars

On-line material: color figures

1. INTRODUCTION

The principal scientific goal of the Diffuse Infrared Background Experiment (DIRBE; Silverberg et al. 1993) aboard the Cosmic Background Explorer (COBE; Boggess et al. 1992) spacecraft was to detect the cosmic infrared background (CIB) in 10 broad bands from the near-infrared (near-IR) at 1.25 μm to the far-IR at 240 μm. The energy in the CIB arises from thermonuclear processes within stars, and to a lesser extent from gravitational energy release by active galactic nuclei (AGNs). At near-IR wavelengths, these energy sources are observed directly in the CIB. At the far-IR wavelengths, the CIB is thermal emission from dust that is heated by either starlight or the emission from AGNs. At all IR wavelengths, the CIB will contain a blend of emission from galaxies at all redshifts. As such, the CIB forms an integral constraint for models of the dominant processes of energy release over the history of the universe.

The DIRBE succeeded in detecting the CIB at 140 and 240 μm (see Hauser & Dwek 2001 for a review). In these bands, local foregrounds from interplanetary dust (i.e., zodiacal light) and our own Galaxy’s interstellar medium (ISM) are only about as bright as the CIB itself. At the shorter wavelengths, Galactic stars and zodiacal emission are brighter than the CIB. The latter foreground can be removed by modeling its spatial and temporal variations over the course of the DIRBE mission. Most of the uncertainties in the removal of the zodiacal light arise from uncertainties in the intensity of its isotropic component. The main uncertainties in the removal of the Galactic stellar emission arise from the removal of the diffuse emission from faint unresolved stars, since bright resolved stars can be readily removed from the DIRBE maps by blanking. Various methods have been used to remove the diffuse Galactic stellar emission component. (1) Hauser et al. (1998) used a faint-star model (Arendt et al. 1998), based on SKY, a star count model developed by Wainscoat et al. (1992). Uncertainties associated with this stellar emission model and the removal of zodiacal light prevented the detection of the CIB at near-IR wavelengths. (2) Dwek & Arendt (1998) created an empirical map of the starlight at 2.2 μm directly from the DIRBE map, and used it as a spatial template for the starlight emission at the other near-IR wavelengths. Their procedure yielded a 3.5 μm CIB estimate that was definitely nonzero, but did not meet strict isotropy requirements. (3) Wright & Reese (2000) used a statistical method, comparing histograms of simulated star counts with histograms of map intensities, to determine the residual background emission at 2.2 and 3.5 μm. (4) Gorjian, Wright, & Chary (2000) subtracted the contribution of stars resolved by ground-based observations at 2.2 and 3.5 μm from a dark patch of the DIRBE sky to estimate the CIB at these wavelengths. Wright (2001) and Cambresy et al. (2001) performed a similar analysis at 1.25 and 2.2 μm using Two Micron All-Sky Survey (2MASS) star counts to subtract the bulk of the Galactic stellar emission. Each of these studies arrived at an estimate of the CIB at these wavelengths. (5) A very different approach to detecting the CIB has been pursued by Kashlinsky et al. (1996a, 1996b) and Kashlinsky & Odenwald (2000). In these studies, the random fluctuations of the confusion limited CIB is measured instead of the mean level. Various measures of these fluctuations (e.g., variance, two-point correlation function, power spectrum) can be related to the mean CIB in the context of a chosen cosmological model. This approach yields results that are independent of the uncertainties in the zero point of the DIRBE data and the foreground emission models, but do rely on accurate assessment and modeling of the instrument and foreground variations.

The positive detection of the near-IR CIB with the Near-Infrared Spectrometer (NIRS) on the Infrared Telescope in Space (IRTS) by Matsumoto et al. (2000) is very important, since it is the only measurement of the absolute CIB intensity based on a data set other than the DIRBE data. However, while the raw data sets are independent measurements, this analysis of the NIRS data did use the Kelsall et al.
model to subtract the zodiacal light emission from the NIRS sky maps.

In this paper, we adopt an empirical approach to modeling the Galactic stellar and ISM emission at 3.5 μm. Observations at another wavelength are used as an emission template which is then scaled by a constant multiplicative factor to represent the 3.5 μm emission. Dwek & Arendt (1998) used this approach to model stellar emission observed by DIRBE at 1.25, 3.5, and 4.9 μm using the 2.2 μm emission as a one-component model template. Puget et al. (1996) and Schlegel, Finkbeiner, & Davis (1998) have used this approach in modeling zodiacal emission at wavelengths above 100 μm with a scaled version of the 25 μm emission. Arendt et al. (1998) modeled ISM emission in this manner using the 100 μm emission as a spatial template at 3.5–240 μm, and, in turn, 21 cm H i emission as a template for 100 μm emission. The common drawback of all these models is that with only a single spatial component, they cannot account for any deviation from the mean spectrum (or scaling factor) of the modeled emission. Arendt et al. (1998) addressed the problem in the context of the 240 μm ISM emission by constructing a two-component model using both the 100 and 140 μm emission as templates. Observationally, this was suggested by the fact that the color-color plot at these wavelengths exhibits a fairly tight correlation, which is associated with variation of the mean temperature of ISM dust grains. Functionally, the use of two templates provides an estimate of both the intensity and the color of the emission at all locations. This enables a better extrapolation of the observed emission to other wavelengths. Equivalently, a two-component model can be viewed as a means of decomposing an emission that arises from two spatially and spectrally distinct phases or populations. Such a decomposition can be applied even if the templates themselves are a combination of the true physical components, as long as they are not combinations in the same proportions. This two-component ISM model was a significantly more accurate representation of the ISM emission, which allowed Hauser et al. (1998) to demonstrate isotropy of the 240 μm residual, thus identifying it as the CIB. Following this example, we now develop an empirical two-component model for the near-IR Galactic stellar emission. One version of this model will ignore extinction effects, and is used only at higher Galactic latitudes. A second version of the model includes adjustments for extinction, and is derived and applied at all latitudes. Without the adjustments, the color variations traced by the two-component model would be caused by interstellar reddening, rather than by intrinsic changes in the stellar emission. For the ISM emission, which is much fainter than the stellar emission in the near-IR, we continue to use the one-component model of Arendt et al. (1998), although here the parameters of the ISM and stellar models will be derived simultaneously.

In § 2 we present our new model for the 3.5 μm zodiacal-light-subtracted emission, in which the stellar component is represented by a linear combination of the extinction-corrected stellar emission at 2.2 and 4.9 μm, the ISM component is modeled using its far-IR emission, and the CIB is assumed to be isotropic. The optical depths at these wavelengths are expressed in terms of the stellar emission at 1.25 and 2.2 μm, where the extinction is largest and the dust emission negligible. The Rieke & Lebofsky (1985) extinction law is used to scale the extinction to other wavelengths. The residual emission, obtained after subtraction of the stellar and ISM emission components from the zodiacal-subtracted 3.5 μm DIRBE maps, should be equal to the 3.5 μm CIB. In practice, we show that with this purely empirical model the 3.5 μm residual is a linear combination of the CIB emission at 2.2, 3.5, 4.9, and 100 μm. In § 3 we report the level and uncertainties of the residual emission, and discuss its isotropy in § 4. These results, combined with those of previous studies, allow us to constrain the CIB at 4.9 μm (§ 5). In § 6, we show that our model leads to a clearer map of the large-scale near-IR ISM emission than has previously been obtained. The results of our paper are briefly summarized in § 7.

2. DECOMPOSITION OF THE 3.5 μm EMISSION

2.1. Modeling Galactic Stellar, ISM, and Extragalactic Components

The observed 3.5 μm emission (after subtraction of the zodiacal light emission by Kelsall et al. 1998) is the sum of Galactic stellar and ISM foreground emission components and a cosmic infrared background,

$$I_{obs}(3.5) = I_{star}(3.5) + I_{ISM}(3.5) + I_{CIB}(3.5).$$

Dwek & Arendt (1998) modeled the 3.5 μm Galactic stellar emission, $I_{star}(3.5)$, by using the observed 2.2 μm emission as an empirical spatial template with a scaling factor determined by a least-squares fit. In the present analysis we use the same general approach of employing the observed emission at other wavelengths as empirical spatial templates of the 3.5 μm Galactic stellar emission, but we make modifications in two respects. First, we use two spatial templates, the 2.2 μm emission and the 4.9 μm emission. This allows a more accurate modeling of the 3.5 μm emission, assuming that there are two distinct components to the stellar emission at each of these wavelengths. In this case, the linear combination of the components that produces the 3.5 μm emission can be expressed as a different linear combination of the 2.2 and 4.9 μm emission. The second change from the Dwek & Arendt (1998) procedure is that here we apply adjustments to the 2.2 and 4.9 μm spatial templates to account for extinction differences between these wavelengths and 3.5 μm. This correction is intended to make the spatial templates (especially at 2.2 μm) more accurate at low latitudes ($|b| < 10^\circ$). The extinction corrections involve the simplifying assumptions that extinction can be treated as a foreground screen, and that the intrinsic background sources have uniform color. Arendt et al. (1994) have previously demonstrated that the near-IR colors of the integrated starlight measured by DIRBE at $|b| < 5^\circ$ can be fitted very well making these assumptions. At high latitudes the extinction is so low at these wavelengths that the correction has no significant effect.

Thus, we represent the observed stellar emission at 3.5 μm as a linear combination of the extinction-corrected emission at 2.2 and 4.9 μm:

$$I_{star}(3.5) = [AI_{star}(2.2)e^{\tau_{2.2}} + BI_{star}(4.9)e^{\tau_{4.9}}]e^{-\tau_{3.5}},$$

where $I_{star}(\lambda)$ and $\tau_\lambda$ are, respectively, the stellar component of the observed emission and the optical depth at the wavelength $\lambda$. With the use of an adopted reddening law to define the wavelength dependence of the extinction, the extinctions in equation (2) can be expressed in terms of the ratio of the...
1.25 to 2.2 \mu m stellar intensity:

$$e^{-(\tau_{1.25} - \tau_{2.2})} \propto \frac{I_{\text{star}}(1.25)}{I_{\text{star}}(2.2)}.$$  

This ratio of the two shortest wavelength DIRBE bands is used because extinction will be strongest, and ISM emission appears to be negligible in these bands (Arendt et al. 1994; Freudenreich 1996). Thus, the actual model for the stellar emission component is given by

$$I_{\text{star}}(3.5) = AI_{\text{star}}(2.2) \left[ \frac{I_{\text{star}}(1.25)}{I_{\text{star}}(2.2)} \right]^\alpha + BI_{\text{star}}(4.9) \left[ \frac{I_{\text{star}}(1.25)}{I_{\text{star}}(2.2)} \right] \beta,$$

where $\alpha = (\tau_{3.5} - \tau_{2.2})/(\tau_{1.25} - \tau_{2.2})$ and $\beta = (\tau_{3.5} - \tau_{1.25})/(\tau_{1.25} - \tau_{2.2})$. The numerical values of $\alpha = -0.317$ and $\beta = 0.210$ are calculated using the Rieke & Lebofsky (1985) reddening law, which has been shown to be a good representation of the extinction observed by DIRBE (Arendt et al. 1994).

Emission from the ISM, the second term in equation (1), is relatively faint at near-IR wavelengths, but it is not negligible at $\lambda \lesssim 3.5 \mu m$. Our model of the ISM emission is the same simple one-component model used by Hauser et al. (1998):

$$I_{\text{ISM}}(3.5) = CI_{\text{ISM}}(100),$$

where $I_{\text{ISM}}(100)$ is the 100 \mu m ISM intensity. This model is obviously a valid approximation at low optical depth, but remarkably, this linear correlation is still observed to exist at very low latitudes where high optical depths might be expected. This is demonstrated and discussed in § 6.

The third component of the observed emission, the CIB, is modeled as an isotropic constant term. While the Galactic stellar and ISM emission components are modeled using their spatial structure, it is the lack of structure that distinguishes the CIB. Even though a few of the nearest, brightest galaxies are resolved by DIRBE’s 0’7 beam (Odenwald, Newmark, & Smoot 1998), we expect that because of stellar confusion and instrumental noise, any detection of the CIB will be isotropic to first order.

Thus, the complete model of the observed 3.5 \mu m emission is represented by

$$I_{\text{obs}}(3.5) = AI_{\text{obs}}(2.2) \left[ \frac{I_{\text{obs}}(1.25)}{I_{\text{obs}}(2.2)} \right]^\alpha + BI_{\text{obs}}(4.9) \left[ \frac{I_{\text{obs}}(1.25)}{I_{\text{obs}}(2.2)} \right] \beta + CI_{\text{ISM}}(100) + IC_{\text{IB}}(3.5).$$  

In the event that the extinction is uniform or negligible, the extinction terms can be rolled into the $A$ and $B$ coefficients, yielding the “no-extinction” model:

$$I_{\text{obs}}(3.5) = AI_{\text{star}}(2.2) + BI_{\text{star}}(4.9) + CI_{\text{ISM}}(100) + IC_{\text{IB}}(3.5).$$

2.2. Interpretation of the Residual Emission

If we had templates of purely stellar emission at 1.25, 2.2, and 4.9 \mu m and pure ISM emission at 100 \mu m, then we could plug these into equations (6) or (7), and perform a least-squares fit to determine the coefficients $A$, $b$, $c$, and the CIB $IC_{\text{IB}}(3.5)$. However, what is actually available is the observed emission at 1.25, 2.2, 4.9, and 100 \mu m, which will contain additional ISM and CIB components. Thus for model 1, equation (7), we evaluate a least-squares fit to determine the coefficients $A'$, $b'$, $c'$, and $d'$ in the equation

$$I_{\text{obs}}(3.5) = A'I_{\text{obs}}(2.2) + b'I_{\text{obs}}(4.9) + C'I_{\text{obs}}(100) + d',$$

which can be expanded (using eq. [1]) as

$$I_{\text{obs}}(3.5) = A'[I_{\text{star}}(2.2) + I_{\text{ISM}}(2.2) + I_{\text{CIB}}(3.5)] + b'[I_{\text{star}}(4.9) + I_{\text{ISM}}(4.9) + I_{\text{CIB}}(4.9)] + C'[I_{\text{ISM}}(100) + I_{\text{CIB}}(100)]$$

$$+ d'.$$

Comparison with equation (7) then shows that

$$A = A',$$
$$B = b',$$
$$C = C',$$
$$I_{\text{CIB}}(3.5) = d' + A'I_{\text{CIB}}(2.2) + b'I_{\text{CIB}}(4.9) + C'I_{\text{CIB}}(100).$$

Thus, we see that in solving equation (8) for $A'$, $b'$, $c'$, and $d'$, instead of solving for $A$, $b$, $c$, and $d$ in equation (7), we derive only a linear combination of the CIB at 2.2, 3.5, 4.9, and 100 \mu m, and not the 3.5 \mu m CIB directly.

Similarly, when model 2 (given by eq. [6]) is evaluated using the observed emission, we start with

$$I_{\text{obs}}(3.5) = A'I_{\text{obs}}(2.2) \left[ \frac{I_{\text{obs}}(1.25)}{I_{\text{obs}}(2.2)} \right]^\alpha + b'I_{\text{obs}}(4.9) \left[ \frac{I_{\text{obs}}(1.25)}{I_{\text{obs}}(2.2)} \right] \beta + C'I_{\text{obs}}(100) + d'.$$

Then, after expansion using equation (1) and comparison with the idealized form in equation (6), we find

$$IC_{\text{IB}}(3.5) = d' + [A'\alpha(\lambda_{12})^\alpha + B'\beta(\lambda_{12})^\beta]IC_{\text{IB}}(1.25)$$

$$+ [A'(1 - \alpha)\alpha(\lambda_{12})^\alpha + B'(1 - \beta)\beta(\lambda_{12})^\beta]IC_{\text{IB}}(2.2)$$

$$+ B'(1 - \beta)IC_{\text{IB}}(4.9) + C'IC_{\text{IB}}(100)$$

after some algebraic reshuffling and keeping only first-order terms. Here $\alpha = I_{\text{obs}}(\lambda_{12})/I_{\text{obs}}(\lambda)$ is the intrinsic color of the stellar emission, which is assumed to be constant over the regions of sky being examined.

3. INTENSITY OF THE RESIDUAL EMISSION

The coefficients $A'$, $b'$, $c'$, and $d'$ were determined with a simple least-squares fit, between the DIRBE zodiacal-light-subtracted maps at 1.25–4.9 and 100 \mu m. These fits minimized the $\chi^2$ parameter measuring the goodness of fit between the data, $I_{\text{obs}}(3.5)$, and the model, right-hand side.
equations (8) or (11). The fit (and all other quantitative analysis) was performed using the approximately equal-area pixels of the native COBE sky-cube projection (Hauser et al. 1997). (Reprojected images in Figs. 1 and 7 are only for display.) The fit used equal weights for all pixels, except for assigning zero weights to the same bright stars and low-latitude emission that were excluded at 3.5 μm in the Hauser et al. (1998) analysis. For the no-extinction model, model 1, we additionally excluded regions at low Galactic latitude ($|b| < 10^\circ$) in order to prevent the model from attempting to match low-latitude color variations at the expense of a good fit at high latitudes. The derived values of the model coefficients and their 1 σ statistical (random) uncertainties are listed in Table 1. In Figure 1, we show the residual map that results from subtraction of the stellar and ISM components of each model from the 3.5 μm emission. These residuals have a mean level of $D'$ (in the unblanked regions). They are depicted on an intensity range comparable to that of the residuals of Hauser et al. (1998) and Dwek & Arendt (1998), which are also shown in Figure 1.

For model 1, the mean intensity of residual emission (eq. [10]) becomes

$$D' = I_{\text{CIB}}(3.5) - 0.445I_{\text{CIB}}(2.2) - 0.220I_{\text{CIB}}(4.9) - 0.00135I_{\text{CIB}}(100)$$
$$= -0.00197,$$

(13)

where all intensities are in MJy sr$^{-1}$, or

$$D' = \nu I_{\text{CIB}}(3.5) - 0.280\nu I_{\text{CIB}}(2.2) - 0.308\nu I_{\text{CIB}}(4.9) - 0.0386\nu I_{\text{CIB}}(100)$$
$$= -1.69,$$

(14)

with $\nu I_{\nu}$ in nW m$^{-2}$ sr$^{-1}$. The above expressions show that the unsubtracted backgrounds in the 2.2, 4.9, and 100 μm components of the models reduce the value of the residual $D'$ from the level of the 3.5 μm CIB.

For model 2, we inserted the numerical values $r_{12} = 1.2$, $r_{41} = 0.25$, and $r_{42} = 0.3$, which were determined at midlatitudes where extinction and the CIB and ISM emission components should be relatively small (e.g., Arendt et al. 1994; Bernard et al. 1994). Then, using the coefficients of the fit for this model, we arrive at

$$D' = I_{\text{CIB}}(3.5) + 0.103I_{\text{CIB}}(1.25) - 0.564I_{\text{CIB}}(2.2) - 0.257I_{\text{CIB}}(4.9) - 0.00123I_{\text{CIB}}(100)$$
$$= -0.00310,$$

(15)

where all intensities are in MJy sr$^{-1}$, or

$$D' = \nu I_{\text{CIB}}(3.5) + 0.0368\nu I_{\text{CIB}}(1.25) - 0.355\nu I_{\text{CIB}}(2.2) - 0.360\nu I_{\text{CIB}}(4.9) - 0.0351\nu I_{\text{CIB}}(100)$$
$$= -2.66,$$

(16)

with $\nu I_{\nu}$ in nW m$^{-2}$ sr$^{-1}$. Not surprisingly, these expressions are similar to the results for model 1, with the addition of a relatively small additive component from the 1.25 μm CIB.

As discussed by Hauser et al. (1998), the systematic uncertainties dominate the random statistical uncertainties in obtaining the mean 3.5 μm residual. Systematic uncertainties include the detector offset and zodiacal light uncertainties, and the uncertainty in the stellar and ISM model developed here. The zodiacal light uncertainties used by Hauser et al. (1998) are equally appropriate here, and are reproduced in Table 2. Detector offset uncertainties are negligible in comparison, and are therefore not listed. The 1 σ uncertainties in the new stellar and ISM models are estimated from the maximum difference of the mean residual intensity of the various high latitude regions listed in Table 3 (see below). As in Hauser et al. (1998), we take the quadrature sum of the zodiacal light and combined stellar and ISM uncertainties to arrive at the total systematic uncertainties, listed for each model in Table 2. The scale factors (weights) that are applied to the zodiacal light uncertainties are the same as those used to scale each wavelength in the construction of the stellar and ISM models.

4. ISOTROPY OF THE RESIDUAL EMISSION

While the residual emission, $D'$, derived here is not the CIB directly, it should still be isotropic because it is a combination of isotropic backgrounds. In fact, $D'$ should be more isotropic than the actual CIB at any single wavelength, because any structure in the CIB is likely to be correlated between wavelengths and at least partially cancel in the construction of $D'$. Therefore, following the example of Hauser et al. (1998), we have examined several different means of assessing the isotropy of the residual emission. In all cases, the key issue is whether or not the data show only the amount of variation expected within the uncertainties. Isotropy of the residual provides more credibly for the accuracy of the subtraction of the foregrounds. It is also a necessary condition for attributing the residual to the combination of CIB backgrounds.

4.1. Mean Patch Brightness

The simplest test of isotropy is comparison of the mean brightness in selected patches. Table 3 lists the brightnesses derived at several of the regions examined by Hauser et al. (1998) and Dwek & Arendt (1998). The differences in brightness among these patches are smaller than in either of the two previous studies, and are smaller than the expected systematic uncertainty (even if only the zodiacal light component of the uncertainty is considered). The patch intensities for model 1 are not quite as uniform as those for model 2, but in both cases the differences are smaller than the expected systematic uncertainties.

### TABLE 1

| Model Version       | A'   | B'   | C/C a | D'   |
|---------------------|------|------|-------|------|
| Dwek & Arendt...... | 0.496| ...  | 0.00183| ...  |
| Model 1..............| 0.445±3×10^{-4} | 0.220±0.001 | 0.00155±7×10^{-6} | -0.00197±6×10^{-5} |
| Model 2..............| 0.467±5×10^{-4} | 0.248±0.002 | 0.00123±8×10^{-6} | -0.00310±1×10^{-4} |

Note.—Values are for $I_{\nu}$ in units of MJy sr$^{-1}$, with ±1 σ statistical uncertainties of the parameters.

C Applies for the Dwek & Arendt model. C' Applies for models 1 and 2.
4.2. Brightness Distributions

The next isotropy test is the examination of the intensity histograms of the residual emission. For a truly isotropic residual, the shape and width of the histograms will reflect only the random noise uncertainties. Histograms constructed for the north and south portions of the high-latitude HQA and HQB regions examined by Hauser et al. (1998) are shown in Figures 2 and 3. The results of fitting Gaussian distributions to the histograms are shown in the figures and listed in Table 4. The new results exhibit smaller dispersion than the previous results, particularly over the relatively large HQA regions. North-south asymmetries in the means of the distributions are also reduced in the new results. Kolmogorov-Smirnov (K-S) tests applied to the distributions indicate that the HQBN residuals are essentially Gaussian for the new results with model 1 and especially model 2, while distributions in the HQBS (and for the Dwek & Arendt 1998 HQB regions) are probably only slightly non-Gaussian. The K-S probabilities of the distributions differing from Gaussian are listed in Table 4. The probability is that of finding a random sampling of the assumed parent Gaussian distribution with a smaller K-S \( D \) parameter than the observed distribution. A value of 1.00 is definitely non-Gaussian; a value of 0.50 indicates that the distribution is indistinguishable from a randomly sampled Gaussian distribution; a probability of 0.0 would indicate a perfect Gaussian distribution with no sampling variation.
### TABLE 2
**Systematic Uncertainties of the Mean 3.5 μm Residual Emission**

| Uncertainty          | Model 1 | Model 2 |
|----------------------|---------|---------|
|                      | \( \sigma \) (nW m\(^{-2}\) sr\(^{-1}\)) | Scale Factor | \( \sigma \) (nW m\(^{-2}\) sr\(^{-1}\)) | Scale Factor |
| Zodiacal light:      |         |         |
| 1.25 \( \mu m \)    | ...     | ...     | 15     | 0.0368 |
| 2.2 \( \mu m \)     | 6       | 0.280   | 6       | 0.355  |
| 3.5 \( \mu m \)     | 2       | 1.00    | 2       | 1.00   |
| 4.9 \( \mu m \)     | 6       | 0.308   | 6       | 0.360  |
| 100 \( \mu m \)     | 6       | 0.0386  | 6       | 0.0351 |
| Stellar and ISM model| 2.2     | 1.00    | 1.7     | 1.00   |
| Total               | 3.9     | ...     | 4.1     | ...    |

![Fig. 1.—Continued](image-url)
TABLE 3  
MEAN 3.5 μm RESIDUAL EMISSION AT SELECT PATCHES

| Patch      | Size/Location | Hauser et al. (1998) | Dwek & Arendt (1998) | Model 1 | Model 2 |
|------------|---------------|----------------------|-----------------------|---------|---------|
| NEP........| $10^\circ \times 10^\circ$ at $\beta = +90^\circ$ | 5.6                  | 5.8                   | -2.3    | -1.8    |
| SEP........| $10^\circ \times 10^\circ$ at $\beta = -90^\circ$ | -2.3                 | 6.6                   | -1.8    | -1.4    |
| NGP........| $10^\circ \times 10^\circ$ at $b = +90^\circ$    | 15.2                 | 11.4                  | -0.9    | -2.2    |
| SGP........| $10^\circ \times 10^\circ$ at $b = -90^\circ$    | 15.9                 | 12.7                  | -1.1    | -2.7    |
| LH ..........| $5^\circ \times 5^\circ$ at $(l, b) = (150^\circ, +53^\circ)$ | 16.1                 | 11.0                  | -0.1    | -1.0    |
| HQA........| $|\|l| > 30^\circ$ and $|\|b| > 25^\circ$ | 10.5                 | 9.9                   | -0.8    | -1.5    |
| HQAN........| $b > +30^\circ$ and $\beta > +25^\circ$       | 11.3                 | 9.5                   | -0.9    | -1.5    |
| HQAS........| $|\|l| < -30^\circ$ and $\beta < -25^\circ$      | 9.7                  | 10.2                  | -0.8    | -1.6    |
| HQB .......| $|\|l| > 60^\circ$ and $|\|b| > 45^\circ$   | 11.4                 | 9.9                   | -0.4    | -1.1    |
| HQBN ........| $b > +60^\circ$ and $\beta > +45^\circ$   | 11.7                 | 9.5                   | -0.5    | -1.1    |
| HQBS ........| $b < -60^\circ$ and $\beta < -45^\circ$      | 11.0                 | 10.2                  | -0.3    | -1.2    |

Note.—Results are for $\nu L_\nu$ in units of nW m$^{-2}$ sr$^{-1}$.

Fig. 2.—Histograms of the residual 3.5 μm intensities in HQAN and HQAS regions from (a, b) the Hauser et al. (1998) results, (c, d) the Dwek & Arendt (1998) results, (e, f) model 1, and (g, h) model 2. The solid lines in (c)–(h) show Gaussian fits to the histograms. The histograms in (a) and (b) are fitted with an additional quadratic base level, which mitigates the effect of the positive tail on the Gaussian fit to the peak. The HQAN results are on the left, and HQAS results are on the right.
4.3. Systematic Spatial Variations

The tests above are necessary conditions for isotropy, but they are insensitive to any anisotropic structure that does not alter the mean level or introduce some skewness or tails to the brightness distributions. A simple means of looking for likely spatial structure is to check for gradients in the residual emission. Figure 4 shows the gradients in the residual emission as a function of the cosecant of Galactic latitude. Data for the north and south hemispheres are shown separately. By this test, the Dwek & Arendt (1998) model removed Galactic emission more effectively than the models used by Hauser et al. (1998). The present models are seen to make further improvements, most dramatically at lower latitudes. The residual emission of model 2 exhibits smaller gradients than that of model 1 over this range of latitudes. Table 5 lists the gradients for the HQA and HQB regions, showing no significant Galactic gradient in the HQB region for the residual emission derived from model 2. The derived gradients in the HQA region are even smaller, but statistically significant, as the region is about 10 times larger. Correlation coefficients are also listed in Table 5. The correlation coefficient should go to 0.0 as the gradient becomes small relative to the variance in the data.

4.4. Two-Point Correlation Functions

The most rigorous test of spatial isotropy that was used by Hauser et al. (1998) is the two-point correlation function. A truly isotropic residual should show no structure above the expected random noise on any spatial scales. The two-point correlation functions for the 3.5 μm residual emission from the present and previous results are shown in Figure 5. We only examine the HQB regions here, since the HQA regions have clearly demonstrated anisotropy in the previous tests. Because the Hauser et al. (1998) results relied on a statistical model for the stellar emission, the mean level but not the detailed structure of the faint stars was removed from the data. Thus, the Hauser et al. results have a much higher “random” noise level than either the Dwek & Arendt (1998) or the present results. The variance of the residual emission in the present results is slightly smaller.
than for the Dwek & Arendt results. The two-point correlation function over the HQB region for model 1 appears to be very nearly random by this test. The model 2 results are not quite as isotropic as the model 1 results, but are distinctly better than the Dwek & Arendt results. Detailed examination of the images (Fig. 1) suggests that the two-point correlation functions in the HQB regions are sensitive to small systematic errors in the structure of the zodiacal light model. With the two-component models used here, zodiacal light errors at different wavelengths partially cancel one another. This cancellation turns out to be slightly more effective for the parameters of model 1 than those of model 2.

5. THE COSMIC IR BACKGROUND AT 4.9 µm

Subtraction of either of the two-component models of stellar emission developed here yields a highly isotropic residual emission map. As shown in 5.3, 2.2, and 3, this residual will contain a combination of the CIB at several wavelengths, and thus is not a direct measure of the CIB at any one wavelength. Still, the relations between the CIB intensities defined by equations (14) and (16) can be used to place constraints on the CIB and its spectrum.

The most straightforward use of the constraints of equations (14) and (16) is to apply known or assumed CIB intensities at several wavelengths in order to derive the unknown CIB intensity at one particular wavelength. This procedure is most useful for estimating the CIB intensity at 4.9 µm, since this is the only near-IR DIRBE band for which no detection of the CIB has been claimed. Various estimates of the CIB at 1–3.5 µm using both COBE/DIRBE and IRTS/NIRS data are in good agreement, apart from systematic differences caused by the method chosen for subtraction of zodiacal light (Hauser et al. 1998; Dwek & Arendt 1998; Wright 2001; Gorjian et al. 2000; Wright & Reese 2000; Matsumoto et al. 2000; Cambresy et al. 2001; see Hauser & Dwek 2001 for a review). Analyses using the Kelsall et al. (1998) zodiacal light model derive a brighter 1–3.5 µm CIB than those using a version of Wright et al.’s zodiacal model with an additional constraint applied to the zodiacal light emission (e.g., Wright & Reese 2000). These systematic differences are about as large as the estimated uncertainties in the zodiacal light models. The CIB intensity at 100 µm appears to be $\nu_{\text{CIB}}(100) \approx 23 \pm 6$ nW m$^{-2}$ sr$^{-1}$ (Hauser et al. 1998; Lagache et al. 2000; Finkbeiner, Davis, & Schlegel 2000). All these prior CIB measurements are listed in Table 6, although not all the estimates are $3\sigma$ detections or have demonstrated isotropy. Still, using these CIB values in equation (14) or (16) leads to the derived estimates of the 4.9 µm CIB that are listed in Table 6. The 4.9 µm results do not depend strongly on the 1.25 or 100 µm backgrounds if they only enter through the small extinction correction and the faint ISM emission, respectively. However, the results are sensitive to the 2.2 and 3.5 µm CIB. Propagation of the uncertainties indicates that this is not a positive detection of the 4.9 µm CIB, and even the $2\sigma$ upper limits on the 4.9 µm CIB are no better than those already established by Hauser et al. (1998) or Dwek & Arendt (1998): less than $41(24.8 \pm 8)$ and less than $36(23.3 \pm 6.4)$ nW m$^{-2}$ sr$^{-1}$, respectively (values in parentheses are measured residual levels and 1 $\sigma$ uncertainties). Figure 6 shows the 4.9 µm residual that we derive, for assumed CIB intensities at 1.25, 2.2, and 3.5 µm as described above. Regardless of which model is used for zodiacal light subtraction, the intensity of the residual emission falls from 1.25 to 3.5 µm, but rises again at 4.9 µm.

The apparent rise at 4.9 µm could indicate thermal dust emission in the CIB spectrum, or else the stellar emission from a burst of star formation at $z \gtrsim 8$. Comparison with galaxy template spectra from Chary & Elbaz (2001) suggest that if the apparent rise at 4.9 µm is from local luminous galaxies containing hot dust, then the associated cold dust emission is likely to exceed the observed far-IR CIB (Fig. 7a, dotted line). Less luminous galaxies will not exceed the far-IR emission, but lack sufficient hot dust to match the near-IR colors of the residual (Fig. 7a, dashed line). Extremely redshifted stellar emission, on the other hand,
would pose no conflict for the far-IR CIB measurements (Fig. 7a, solid line). However, the intensity of this emission would be in conflict with the indirect upper limits on the CIB placed by the TeV γ-ray measurements and estimates of the CIB fluctuations (see Hauser & Dwek 2001 and references therein). These upper limits are typically 5–15 nW m⁻² sr⁻¹ at wavelengths above 5 μm. In addition, the integrated intensity (1–100 μm) of this component would be \(~57\) nW m⁻² sr⁻¹. Production of this integrated intensity would require a constant luminosity density of \(\mathcal{L} \approx\).
intense burst of star formation at \( z = 8 \) would deplete the hydrogen mass fraction by \( \Delta X \approx 0.1 \pm 0.01 \), which exceeds the solar value of \( \Delta X_{\odot} \approx 0.06 \). The star formation rate would be lower if only high-mass stars were formed, but the metal production is still directly linked to the luminosity density.

Instead of implying interesting phenomena at high redshifts, it is more likely that the 4.9 \( \mu m \) rise indicates an incomplete subtraction of the Galactic or zodiacal foregrounds (Fig. 7b). A Galactic origin for the rise seems unlikely, however, since it would require the 3.5 and 4.9 \( \mu m \) emission of the ISM to have been underestimated by a factor of 10 or more, or it would require the presence of some unknown discrete sources with spectra that peak at \( \sim 5-10 \) \( \mu m \) \( (T \approx 300-600 \) K) and a distribution that appears isotropic as viewed from the Galactic location of the Sun. The rise is more likely caused by unsubtracted zodiacal light. The zodiacal light spectrum is actually a suspiciously good match to the residual emission reported by Hauser et al. (1998) from 1.25 to 100 \( \mu m \), and to the near-IR CIB spectrum reported by others. The elevated 4.9 \( \mu m \) emission should therefore serve as a warning that residual zodiacal light emission may also affect estimates of the CIB at shorter wavelengths. The magnitude of this effect is difficult to estimate because the zodiacal light is thermal emission at 4.9 \( \mu m \) and scattered light at shorter wavelengths. Uncertainties in the spatial distribution of the dust may produce correlated errors at 4.9 \( \mu m \) and shorter wavelengths, whereas uncertainties in the optical properties of the grains may not.

Recent measurements of the optical extragalactic background light (EBL) by Bernstein, Freedman, & Madore (2002) indicate that high estimates of the 1.25 \( \mu m \) CIB (e.g., Matsumoto et al. 2000; Cambresy et al. 2001) may be affected by systematic errors. At face value, the results would require an unphysically sharp rise in the CIB spectrum from 0.8 to 1.1 \( \mu m \). An error in the 1.25 \( \mu m \) CIB would only alter our estimate of the 4.9 \( \mu m \) CIB by 1–2 nW m\(^{-2}\) sr\(^{-1}\), but this apparent discrepancy provides additional hints at the likelihood and size of systematic errors in the analysis of the near-IR CIB and/or the optical EBL.

In the near future, lower limits on the CIB that will be obtained through deep galaxy counts with the Infrared Array Camera (IRAC) on the Space Infrared Telescope Facility (SIRTF) at 3.6, 4.5, 5.8, and 8 \( \mu m \) should clearly
reveal whether or not the cosmic star formation rate rises sharply at high $z$ (Fazio et al. 1998).

6. NEAR-IR EMISSION OF THE INTERSTELLAR MEDIUM

Studies of the relatively faint emission from the diffuse Galactic ISM at 3.5 and 4.9 $\mu$m require an accurate method of separating it from the brighter stellar emission. Freudenreich (1996) shows that emission of the ISM can be traced to high latitudes using the 3.5/2.2 $\mu$m colors, which are relatively constant for the stellar population, but are redder where ISM emission is present. Arendt et al. (1998) correlated the variations in the reddening-free near-IR colors with 100 $\mu$m ISM emission to derive the 3.5/100 $\mu$m and the 4.9/100 $\mu$m colors of the ISM. However, the derivation of these colors was restricted to very low Galactic latitudes. Now, with the models developed here, we can subtract the stellar emission directly, producing a map of the 3.5 $\mu$m ISM emission instead of only an average near-IR color. The 3.5 $\mu$m ISM emission derived from subtracting the stellar emission of model 2 is shown in Figure 8. Comparison with the 100 $\mu$m emission reveals an excellent match of features down to the effective noise level of the 3.5 $\mu$m map. The linear correlation of the 100 and 3.5 $\mu$m emission is plotted in Figure 9 for regions $|b| < 20^\circ$. The line plotted over the data is not a direct fit to this correlation, but rather the expected relation between the 3.5 and 100 $\mu$m emission implied by the coefficients of model 2. The inset shows that this same linear trend fits all the way down to the faintest ISM emission, despite the fact that the faint emission has relatively little weight in determining the model coefficients. Higher latitude emission is all faint, and adds noise to the correlation at low intensities, but it still appears to follow the same correlation.

The coefficients $C'$ listed in Table 1 for models 1 and 2 must be converted to the actual ISM color through the relation

$$I_{\text{ISM}}(3.5) / I_{\text{ISM}}(100) = C' + B I_{\text{ISM}}(4.9) / I_{\text{ISM}}(100),$$

(17)

because the observed 4.9 $\mu$m emission, used as a stellar template, includes weak ISM emission as well as starlight (see § 2.2). ISM emission at 2.2 $\mu$m has not been detected and thus in not included in this conversion. The near-IR colors of the ISM emission determined by Arendt et al. (1998) are consistent with this relation for the coefficients of either model 1 or model 2.

The strong correlation between 3.5 and 100 $\mu$m ISM emission at low latitudes as well as high latitudes indicates that, in the diffuse ISM, the distribution of the very small grains or PAHs responsible for the 3.5 $\mu$m emission is not very different from that of the larger grains which produce most of the 100 $\mu$m emission. Previous studies by Giard et al. (1989) and Tanaka et al. (1996) have identified a similarly good
correlation between the 3.3 μm PAH feature and 12 and 100 μm emission using data sets that were less sensitive or more restricted in coverage than the DIRBE data. The fact that the correlation is so tight despite Galactic gradients in the interstellar radiation field (ISRF), which varies in intensity by factors of \(\sim 3–5\) on a scale of several kpc (Mathis, Mezger, & Panagia 1983; Sodroski et al. 1997), can be explained by considering the heating of the dust grains. First, the 3.5 μm intensity of the small grains or PAHs will be proportional to the UV intensity of the ISRF, while the spectral shape of the emission is essentially constant. Second, the emission of large grains immersed in the typical ISRF peaks at wavelengths slightly longer than 100 μm. Being near the peak of the Planck function, there is a wide range (a factor of \(\gtrsim 10^2\)) of ISRF intensity, \(I_{\text{ISRF}}\), over which the quantity \(I_{\text{ISM}}(100)/I_{\text{ISRF}}\) varies by no more than a factor of 2. Therefore, over a wide range of ISRF intensity, both the 3.5 and 100 μm emission are roughly proportional to the intensity of the ISRF. Detailed modeling of the emission by Li & Draine (2001) shows that the ratio of \(I_{\text{ISM}}(3.5)/I_{\text{ISM}}(100)\) is expected to vary by less than 20% for an ISRF scaled from 1 to 30 times its local intensity (see their Fig. 13). Because the large-scale variation of the ISRF is only a fraction of this range, the ratios \(I_{\text{ISM}}(3.5)/I_{\text{ISM}}(60)\) and \(I_{\text{ISM}}(3.5)/I_{\text{ISM}}(240)\) are also observed to be relatively constant, and correlations of \(I_{\text{ISM}}(3.5)\) with \(I_{\text{ISM}}(60)\) or \(I_{\text{ISM}}(240)\) are similar in appearance to Figure 9.

7. SUMMARY

We have developed an empirical model of the 3.5 μm Galactic and extragalactic emission seen by DIRBE. The Galactic stellar emission is modeled with two spatial components. The Galactic ISM emission is modeled with a single spatial template. The residual emission after subtraction of the Galactic emission is isotropic to a high degree, but...
without a significantly positive intensity. However, because our model uses the observed emission in other IR bands as spatial templates, the residual should be a linear combination of the CIB at several wavelengths. Existing estimates of the CIB at 1.25, 2.2, 3.5, and 100 $\mu$m can be combined to derive a new (but highly uncertain) estimate of the CIB intensity at 4.9 $\mu$m, which suggests that the CIB intensity may begin to increase at wavelengths above 3.5 $\mu$m. Such a rise in the spectrum of the residual emission after subtraction of the foregrounds may indicate interesting physics in the spectrum of the CIB, but is more likely to simply indicate systematic errors in the subtraction of the zodiacal and/or Galactic foreground emission.

We thank the anonymous referee for a careful and helpful review of this paper. The National Aeronautics and Space Administration/Goddard Space Flight Center (NASA/GSFC) was responsible for the design, development, and operation of the COBE. GSFC was also responsible for the development of the analysis software and the production of the mission data sets. This work was supported by the NASA ADP program, grant NASW-99228.

REFERENCES

Arendt, R. G., et al. 1994, ApJ, 425, L85
———. 1998, ApJ, 508, 74
Bernard, J. P., Boulanger, F., Désert, F. X., Giard, M., Helou, G., & Puget, J. L. 1994, A&A, 291, L5
Bernstein, R. A., Freedman, W. L., & Madore, B. F. 2002, ApJ, 571, 56
Boggess, N., et al. 1992, ApJ, 397, 420
Cambrésy, L.,Reach, W. T.,Beichman, C. A., & Jarrett, T. H. 2001, ApJ, 555, 563
Chary, R. R., & Elbaz, D. 2001, ApJ, 556, 562
Dwek, E., & Arendt, R. G. 1998, ApJ, 508, L9
Fazio, G., et al. 1999, Proc. SPIE, 3354, 1024
Finkbeiner, D. P., Davis, M., & Schlegel, D. J. 2000, ApJ, 544, 81
Freudenreich, H. T. 1996, ApJ, 468, 663
Giard, M., Pajot, F., Lamarre, J. M., Serra, G., & Caux, E. 1989, A&A, 215, 92
Gorjian, V., Wright, E. L., & Chary, R. R. 2000, ApJ, 536, 550
Hauser, M. G., & Dwek, E. 2001, ARA&A, 39, 249
Hauser, M. G., Kelsall, T., Leisawitz, D., & Weiland, J., eds. 1997, COBE Diffuse Infrared Background Experiment (DIRBE) Explanatory Supplement (COBE Ref. Pub. No. 97-A; Grenbelt: NASA/GSFC)
Hauser, M. G., et al. 1998, ApJ, 508, 25
Kashlinsky, A., Mather, J. C., & Odenwald, S. 1996a, ApJ, 473, L9
Kashlinsky, A., Mather, J. C., Odenwald, S., & Hauser, M. G. 1996b, ApJ, 470, 681
Kashlinsky, A., & Odenwald, S. 2000, ApJ, 528, 74
Kelsall, T., et al. 1998, ApJ, 508, 44
Lagache, G., Haßner, L. M., Reynolds, R. J., & Tufte, S. L. 2000, A&A, 354, 247
Lanzetta, K. M., Yahata, N., Pascarelle, S., Chen, H.-W., & Fernández-Soto, A. 2002, ApJ, 570, 492
Li, A., & Draine, B. T. 2001, ApJ, 554, 778
Mathis, J. S., Mezger, P. G., & Panagia, N. 1983, A&A, 128, 212
Matsumoto, T., et al. 2000, in ISO Surveys of a Dusty Universe ed. D. Lemke, M. Stickel, & K. Wilke (Berlin: Springer), 96
Odenwald, S., Newmark, J., & Smoot, G. 1998, ApJ, 500, 554
Olive, K. A., Steigman, G., & Walker, T. P. 2000, Phys. Rep., 333, 389
Puget, J.-L., Abergel, A., Bernard, J.-P., Boulanger, R., Burton, W. B., Désert, R.-X., & Hartmann, D. 1996, A&A, 308, L5
Rieke, G. H., & Lebofsky, M. J. 1985, ApJ, 288, 618
Schlegel, D. J., Finkbeiner, D. P., & Davis, M. 1998, ApJ, 500, 525
Silverberg, R. F., et al. 1993, Proc. SPIE, 1993, 180
Sodroski, T. J., Odegard, N., Arendt, R. G., Dwek, E., Weiland, J. L., Hauser, M. G., & Kelsall, T. 1997, ApJ, 480, 173
Tanaka, M., Matsumoto, T., Murakami, H., Kawada, M., Noda, M., & Matsuura, S. 1996, PASJ, 48, L53
Wainscoat, R. J., Cohen, M., Volk, K., Walker, H. J., & Schwartz, D. E. 1992, ApJS, 83, 111
Wright, E. L. 2001, ApJ, 553, 538
Wright, E. L., & Reese, E. D. 2000, ApJ, 545, 43