COSMOLOGICAL CONSTANT OR INTERGALACTIC DUST? CONSTRAINTS FROM THE COSMIC FAR-INFRARED BACKGROUND

ANTHONY AGUIRRE
Department of Astronomy, Harvard University, 60 Garden Street, Cambridge, MA 02138; aaguirre@cfa.harvard.edu

AND

ZOLTAN HAIMAN
NASA/Fermilab Astrophysics Center, Fermi National Accelerator Laboratory, Batavia, IL 60510; zoltan@fnal.gov

Received 1999 July 1; accepted 1999 November 3

ABSTRACT

Recent observations of Type Ia supernovae (SNe) at redshifts 0 < z < 1 reveal a progressive dimming that has been interpreted as evidence for a cosmological constant of \( \Omega_\Lambda \approx 0.7 \). An alternative explanation of the SN results is an open universe with \( \Omega_\Lambda = 0 \) and the presence of \( \gtrsim 0.1 \) \( \mu \)m dust grains with a mass density of \( \rho_{\text{dust}} \sim \text{a few} \times 10^{-5} \) in the intergalactic (IG) medium. The same dust that dims the SNe absorbs the cosmic UV/optical background radiation around \( \sim 1 \) \( \mu \)m, and reemits it at far-infrared (FIR) wavelengths. Here we compare the FIR emission from IG dust with observations of the cosmic microwave (CMB) and cosmic far-infrared backgrounds (FIRB) by the DIRBE/FIRAS instruments. We find that the emission would not lead to measurable distortion of the CMB, but would represent a substantial fraction (\( \gtrsim 75\% \)) of the measured value of the FIRB in the 300–1000 \( \mu \)m range. This contribution would be marginally consistent with the present unresolved fraction of the observed FIRB in an open universe. However, we find that IG dust probably could not reconcile the standard \( \Omega = 1 \) CDM model with the SN observations, even if the necessary quantity of dust existed. Future observations, capable of reliably resolving the FIRB to a flux limit of \( \sim 0.5 \) mJy, along with a more precise measure of the coarse-grained FIRB, will provide a definitive test of the IG dust hypothesis in all cosmologies.

Subject headings: cosmic microwave background — cosmology: observations — cosmology: theory — galaxies: evolution — galaxies: formation

1. INTRODUCTION

One of the most remarkable results in recent observational cosmology is the detection of Type Ia supernovae (SNe Ia) at cosmological distances. Comparing the Hubble diagram of these \( \sim 50 \) SNe with the predictions of classical cosmological models strongly favors models with acceleration in the cosmic expansion, presumably due to a significant cosmological constant (Perlmutter et al. 1999; Riess et al. 1998). Given the far-reaching implications of this result, it is important to assess the possible systematic effects that could mimic the behavior of cosmic acceleration, and thus allow cosmologies without a cosmological constant.

Intergalactic (IG) dust could provide such a systematic effect. The amount of dust required to fully account for the systematic dimming of SNe at high redshift in an open universe is \( \Omega_{\text{dust}} \sim \text{a few} \times 10^{-5} \) (Aguirre 1999a; Aguirre 1999b, hereafter A99). If this quantity of dust had the same composition as interstellar dust in the Milky Way, it would cause a significant reddening in the SN spectra, which is not observed. However, A99 showed that the removal of small dust grains during their ejection from galaxies into the IG medium could bias the composite dust cross section to cause little reddening for a given amount of extinction. A99 presented specific models for the evolution of the IG dust that are consistent with the observed lack of reddening, but provide the amount of extinction needed to fully account for the SNe results in an open universe.

In the present paper, we study the observational consequences of the IG dust hypothesis in far-infrared (FIR) wavelength bands. As is well known from previous studies, IG dust would efficiently absorb the UV/optical flux of galaxies and quasars and reradiate this energy in the FIR (e.g., Wright 1981; Bond, Carr, & Hogan 1991; Loeb & Haiman 1997). Although studied in great detail in these works, this effect is at present of renewed interest, owing to recent direct estimates of the global average comoving star formation rate (SFR) in the universe (e.g., Madau 1999, hereafter M99) and determinations of the extragalactic UV/optical background (UVB; Bernstein 1997), as well as of the cosmic far-infrared background (FIRB; see Fixsen et al. 1998; Puget et al. 1996). We thus have, for the first time, a measurement of both the UV reservoir available for dust absorption and the background flux at the wavelengths at which this energy would be emitted by the dust.

In this paper, we compute contributions to the FIRB and CMB arising from IG dust, and compare these to the measured values. Our aim is to assess whether the amount and type of dust that would explain the SNe results in an \( \Omega_\Lambda = 0 \) universe is compatible with these new observations.

At present, the source of the observed FIRB remains unclear, although rapid progress is being made using deep observations with SCUBA. Barger, Cowie, & Sanders (1999a) and Hughes et al. (1998) have detected a population of discrete IR sources whose cumulative flux down to \( \sim 2 \) mJy accounts for at least 20%–30% of the FIRB at 850 \( \mu \)m. The gravitationally lensed sample of Blain et al. (1999a, 1999b) goes farther, down to \( \sim 1 \) mJy, but is more uncertain because of the lensing model and small number of detections. It is therefore currently uncertain whether the counts continue to sufficiently faint flux to account for all of the FIRB.

Furthermore, we lack information on the spectra of these
sources at wavelengths other than 850 \( \mu m \). Although the full FIRB can be explained theoretically in semianalytic galaxy formation models (Guiderdoni et al. 1998), this requires the somewhat ad hoc postulate that the ratio of the number of ultraluminous infrared galaxies (ULIGs) to that of normal optical galaxies increases rapidly with redshift. In summary, according to our present knowledge, 70\%–80\% of the FIRB could still be contributed by diffuse emission from IG dust, but this may change very quickly.

As in the case of the FIRB, the nature of the observed UVB is unclear. The directly observed values at 0.55 and 0.8 \( \mu m \) are \( 20 \pm 10 \text{nW m}^{-2} \text{sr}^{-1} \) (Bernstein 1997). By comparison, a recent compilation of ground-based galaxy counts and a survey of galaxies in the Hubble Deep Field (HDF) (Vogeley 1997) has yielded an estimate for the evolution of the global star formation rate in the universe between \( 0 < z \leq 5 \). The UVB that follows from a census of these galaxies is around \( \sim 12 \text{nW m}^{-2} \text{sr}^{-1} \) (M99; Pozzetti et al. 1998), a factor of \( \sim 2 \) smaller than the observed value. A natural explanation for the difference would be if the remaining \( \sim 50\% \) of the UVB were contributed by faint, undetected galaxies; however, this appears to violate limits from the fluctuations in the UVB measured in the HDF (Vogele 1997). Despite these uncertainties, the approximate amplitude of the UVB allows us to compute useful estimates of the contribution of IG dust to the FIRB.

The rest of this paper is organized as follows. In \( \S \hspace{1pt} 2 \) we summarize our model for the amount and type of IG dust; in \( \S \hspace{1pt} 3 \) we describe our assumptions concerning the redshift evolution of both the UV emission and dust production, and outline our calculation methods; and in \( \S \hspace{1pt} 4 \) we discuss limits from existing FIRAS observations of the CMB. Section 5 contains our main results on the contribution to the FIRB from IG dust, as well as hopes for future tests of the dust hypothesis for the SN results; and in \( \S \hspace{1pt} 6 \) we summarize our conclusions. Unless otherwise stated, in this paper we adopt an open cosmology with total matter density \( \Omega = 0.2 \) and Hubble constant \( h_{50} = 1 \).

2. IG DUST MODEL

The model adopted here for IG dust is discussed at length in A99; here we provide only a brief summary. The model is based on the following method of estimating the total IG dust density, \( \Omega_{\text{dust}}(z) \): we first estimate the total metal density, \( \Omega_{\text{d}}(z) \), then multiply this figure by the fraction \( f_{\text{d}} \) of these metals that lie outside galaxies and then by the fraction \( d_{\text{m}} \) of IG metals contained in IG dust.

As shown in A99, both a direct integration of the SFR (with an assumption of the metals produced for each star formed) and fossil evidence from clusters indicate that \( \Omega_{\text{d}}(z \lesssim 0.5) \approx (2.5–5) \times 10^{-4} \) (adjusted from A99 for \( h_{50} = 1 \)). These estimates follow from conservational assumptions: that stars in cluster galaxies have the same IMF as those in field galaxies, that there is not a dominant population of unobserved galaxies, etc.; see A99.

Measurements of the metallicity of intracluster gas indicate that a fraction \( f_{\text{d}} \approx 75\% \) of a typical cluster’s metals lie in the intracluster medium (e.g., Renzini 1997), presumably removed from the galaxies by some combination of winds, dust expulsion, ram pressure stripping, and tidal disruption/merging of galaxies. While ram pressure stripping and mergers may be more effective at removing metals from cluster galaxies, it is nevertheless likely that the figure \( f_{\text{d}} \approx 75\% \) applies to the field galaxies, since a much smaller value, together with the estimate of \( \Omega_{\text{d}} \gtrsim 10^{-4} \), would imply that field galaxies have mean metallicities several times solar, contrary to observation.

To estimate the fraction \( d_{\text{m}} \) of IG metals in dust, we assume a value of \( \sim 0.5 \) for metals leaving the galaxy, as applies to the interstellar medium of both typical galaxies and perhaps even to damped Lyx systems (Pei, Fall & Hauser 1999). Some fraction \((1 - f)\) by mass of this dust must be destroyed either during ejection or in the IG medium, giving \( d_{\text{m}} \approx 0.5f \). Combining these figures, we estimate an IG dust density at \( z \leq 0.5 \) of

\[
\Omega_{\text{dust}} \approx (9.4–18.8)f \times 10^{-5}.
\]

To fix both \( f \) and the dust properties, we adopt the two-component Draine & Lee (1984, hereafter DL) dust model\(^1\) of silicate and graphite spheres with size distribution \( N(a)da \propto a^{-3.5} \), \( 0.005 \leq a \leq 0.25 \text{ \mu m} \) (Mathis, Rumpl, & Nordsieck 1977, hereafter MRN) as representative of galactic dust. We further assume that IG dust differs from MRN dust due to the removal (by the selective ejection of large grains and/or the selective destruction of small grains by sputtering) of the small-size end of the grain size distribution. In this paper we use absorption and scattering curves as calculated in Laor & Draine (1993), and the truncated MRN distribution with \( a_{\min} = 0.1 \text{ \mu m} \); the minimal grain size (which corresponds to \( f \approx 0.4 \)) is chosen to give dust that is gray enough not to overredden the supernovae (A99). Note that our results should not be sensitive to our adoption of the Milky Way dust cross section; e.g., LMC dust differs from Milky Way dust mainly at short wavelengths, where the opacity has in any case been modified by removing the small grains. Silicate and graphite grains are assumed to have equal mass densities, and the total dust density is chosen, according to the cosmology, as that sufficient to reconcile the chosen cosmology with the supernova results. For example, \( \Omega = 0.2 \) requires \( \sim 0.15–0.2 \) mag of extinction at \( z \sim 0.5 \) and hence \( \Omega_{\text{dust}} \sim (5.5–7) \times 10^{-5} \) to be consistent with the observations.

3. METHOD OF CALCULATION

In estimating the contribution from IG dust to the FIRB and the CMB, we follow the methods of Wright (1981; see also Loeb & Haiman 1997). We define the comoving number density of photons at redshift \( z \) and comoving frequency \( \nu \) as

\[
N_{\nu}(z) = \frac{4\pi}{hc(1+z)} J_{\nu,1+z}(z),
\]

where \( J_{\nu}(z) \) is the usual specific intensity of the background radiation field in physical (noncomoving) units of ergs cm\(^{-2}\) s\(^{-1}\) Hz\(^{-1}\) sr\(^{-1}\). The evolution of \( N_{\nu}(z) \) with redshift is then described by the cosmological radiative transfer equation

\[
- \frac{dN_{\nu}(z)}{dz} = \frac{c dt}{dz} [J_{\text{tot},\nu}(z) - \alpha_{\nu}(z) N_{\nu}(z)],
\]

where \( J_{\text{tot},\nu} = J_{\text{phot},\nu} + J_{\text{dust},\nu} \) is the total comoving emission coefficient, including both the direct light of UV sources, \( J_{\text{phot},\nu} \) (see eq. [8] below), and thermal dust emission, \( J_{\text{dust},\nu} \), from

\(^1\) The effects are, of course, somewhat dependent upon the grain model; see A99 for discussion.
dust. As discussed in § 2, we assume that dust is composed of graphite and silicate grains, so that the total dust absorption coefficient, \( \alpha \), is given in units of cm\(^{-1}\) by

\[
\alpha(z) = \alpha_{\text{Si, v}}(z) + \alpha_{\text{Gr, v}}(z) = \frac{\rho_{\text{Si}} + \rho_{\text{Gr}}}{\kappa_{\text{Si, v}}(1 + z) + \kappa_{\text{Gr, v}}(1 + z)} ,
\]

for a total mass density of \( \rho_{\text{Si}} + \rho_{\text{Gr}} = (\Omega_{\text{Si}} + \Omega_{\text{Gr}}) \rho_{\text{crit, 0}}(1 + z)^3 \) in dust, where the \( \kappa \)'s are the dust opacities in units of cm\(^2\) g\(^{-1}\). Note that by assumption, \( \Omega_{\text{Si}} = \Omega_{\text{Gr}} \). The total comoving dust emission coefficient is then

\[
f_{\text{dust, v}} = f_{\text{Si, v}} + f_{\text{Gr, v}} = \frac{8 \pi v^3}{c^5} \left\{ \frac{\alpha_{\text{Si, v}}(z)}{\exp \left[ h v (1 + z)/k_B T_{\text{Si}} \right] - 1} + \frac{\alpha_{\text{Gr, v}}(z)}{\exp \left[ h v (1 + z)/k_B T_{\text{Gr}} \right] - 1} \right\} .
\]

The silicate and graphite grains are assumed to be separately in thermal equilibrium with the total background radiation (CMB + UV sources), so that the grain temperatures, \( T_i \), are obtained by equating the total amount of absorption and emission:

\[
\int_0^\infty dv \alpha_i(z) N_i(z) = \int_0^\infty dv j_i(z) ,
\]

where \( i = \text{Si or Gr} \).

The infrared background spectrum arises from the re-emission of UV light absorbed by dust. The two main factors determining the FIRB are therefore the evolution of the UV emissivity, \( j_{\ast, v} \), from stellar sources (determining the dust temperature), and the evolution of the dust density, \( \Omega_{\text{dust}} = \Omega_{\text{Si}} + \Omega_{\text{Gr}} \), determining the overall amplitude of the emissivity. For the UV production rate, here we adopt the global average star formation rate as determined recently by Madau et al. (1998). We ignore any additional UV flux from quasars; at the redshifts of interest here (\( z \lesssim 5 \)), the contribution to the UV background from the known population of quasars is less than 20% (M99). Note, however, that a population of faint, undetected quasars could contribute substantially to the UV background (Haiman & Loeb 1998).

For simplicity, we assume further that the average spectrum from the stellar UV sources is described by that of blackbody radiation at a temperature of \( T = 9000 \) K. This is a reasonably good approximation to the continuum in the composite spectra found in the population synthesis models of G. Bruzual & S. Charlot (in preparation), although the pure blackbody spectrum is somewhat narrower. The blackbody also falls below the UV background flux limit at the shortest wavelengths (\( \lambda \sim 0.1 \) \( \mu \)m); see also § 5.2. Our results below depend primarily on the total amount of stellar light absorbed by the dust, and are insensitive to the precise shape of the UV spectrum (see detailed discussion below). With the above assumptions, the stellar emissivity is given by

\[
j_{\ast, v}(z) = A_{\ast} \dot{\rho}_v(z) B_v(1 + z)(T = 9000 \) K) ,
\]

where \( B_v \) is the Planck function, and \( \dot{\rho}_v(z) \) is the star formation rate in Madau, Pozzetti, & Dickinson (1998), converted from their standard \( \Omega = 1 \) cosmology to the open \( \Omega = 0.2 \) model assumed here, using the multiplicative factor \((dv/d\lambda^2_0)/(dv/d\lambda_A)\), where \( dv \) and \( d\lambda \) are the volume elements and luminosity distances, respectively, in the two cosmologies (Eisenstein 1997).

The overall normalization constant \( A_{\ast} \) is somewhat uncertain. M99 argues that the total UV produced by stars is a factor of \( \sim 2 \) smaller than the recent measurement of the extragalactic UV background, \( vJ_{\ast} = 20 \) nW m\(^{-2}\) sr\(^{-1}\) at 0.55 \( \mu \)m, by Bernstein (1997). It is not clear what is the reason for this discrepancy is; the shortage of UV could be provided by additional faint galaxies or quasars (however, see Vogele 1997). Here we take the simplest approach, and adjust the normalization constant \( A_{\ast} \) so that the measured value of 20 nW m\(^{-2}\) sr\(^{-1}\) for the UV background at 0.55 \( \mu \)m is exactly reproduced (taking into account dust absorption). Given the shortage of UV provided by the known stellar population, we will also examine below a model normalized to 10 nW m\(^{-2}\) sr\(^{-1}\), the lower end of the 1 \( \sigma \) range quoted by Bernstein (1997). This also lies above the lower limits on the UV background derived from galaxy counts in the Hubble Deep Field (Pozzetti et al. 1998; see Fig. 1). Note that we have assumed a specific spectral shape

\[\text{Fig. 1.—Top: Full } z = 0 \text{ output spectrum (solid line) for our fiducial model, with the best-fit CMB (top dotted line) subtracted. Also shown are the fitted } v^2B_v \text{ component (bottom dotted line), the FIRAS-detected FIRB } \pm 1 \text{ bounds (dashed line), DIRBE FIRB detections (crosses) and upper limits (down arrows), the UVB detections (triangles) and HDF-derived lower limits (up arrows), and the Voyager FUV upper limit (diamond). Bottom: Spectrum with both CMB and } v^2B_v \text{ component subtracted (solid and dashed lines, respectively). Vertical dotted lines represent the wavelength range over which the FIRAS distortion limit analysis was performed; horizontal dotted line indicates the rms of the residuals in the FIRAS data. The features in the 500–5000 } \mu \text{m range indicate the level of numerical noise in our calculations.}\]
and redshift evolution of the UV emissivity. We again emphasize that our results are insensitive to the detailed shape of the UV flux around 1 μm and depend only on the total amount of UV light absorbed; this is demonstrated by a model examined below with a more realistic spectrum obtained from population synthesis models (G. Bruzual & S. Charlot in preparation) and models with SF histories different from M99. As mentioned above, the difference between the background inferred from the observed star formation rate (i.e., by direct integration of $\dot{\rho}_{\star}$) and an empirical UV flux per stellar mass ratio, and the measured value of 20 nW m$^{-2}$ sr$^{-1}$ could be provided by undetected quasars, or other as yet undiscovered sources. As long as the redshift evolution of these sources does not depart significantly from the range of our assumed $\dot{\rho}_{\star}(z)$, our results below would remain valid.

Next, we assume that the same stellar population that produces the UV background is the source of IG dust. Under this simple assumption, the mass density of dust increases in proportion to the mass density in stars,

$$\Omega_{\text{dust}}(z) = A_{\text{dust}} \int_{\dot{\rho}_{\star}(z)}^{\dot{\rho}_{\star}(z=0)} dt \dot{\rho}_{\star}(z),$$

and we assume further that $\Omega_{\text{dust}}(z) = \Omega_{\text{dust}}/2$ (as discussed in §5, the exact value of this ratio is not crucial). The normalization constant $A_{\text{dust}}$ is chosen by requiring the total optical depth due to dust absorption + scattering between $z = 0$ and $z = 0.5$ to be $\sim 0.15$. As we argued in §2 above, this is the amount needed to account for the SN results (A99). This normalization corresponds to $\Omega_{\text{dust}}(z = 0) \sim 5 \times 10^{-5}$. Adding to the arguments given in §2, we note that this dust density fits in comfortably with the amount of dust expected to be produced in normal stars. For instance, assuming that each Type II SN ($M_* \geq 8 M_\odot$) yields 0.3 $M_\odot$ of dust, adopting a Scalo IMF, and normalizing $\Omega_{\star}(z = 0) = 0.004$, we obtain $\Omega_{\text{dust}}(z = 0) = 5 \times 10^{-5}$ (cf. Loeb & Haiman 1997). This estimate does not account for dust trapped in galaxies or destroyed, but it is also a lower limit, since it only includes the dust formed in supernovae, and not that formed in (for example) dense clouds or carbon stars.

We note that although stellar dust production cannot occur instantaneously with star formation, the relevant timescales are likely to be much shorter than the Hubble time at redshifts of interest. Type II SNe produce dust in a few million years, while the lifetime of carbon stars (believed to be dominating the dust budget in the Milky Way; see Gehrz 1989) is still only $\sim 1$ Gyr. The ejection timescale for dust leaving spiral galaxies is probably between 100 and 1000 Myr (A99). We have found that incorporating a delay of $\sim 1$ Gyr between star formation and dust production into equation (9) does not change our results below by more than a few percent.

Equations (2)–(9), together with the initial condition that $N_\star$ at some high redshift is equal to the pure CMB, with $T_{\text{CMB}} = 2.728(1 + z)$ K, determine the redshift evolution of the full background spectrum.

4. EXISTING FIRAS LIMITS

Any existing IG dust component will process some UV/optical energy into the FIR/microwave. As a result, some (perhaps vanishingly small) fraction of the observed CMB is due to emission from IG dust. This contribution has been studied a number of times previously. Some authors have investigated the possibility that the CMB is entirely dust-processed emission from astrophysical objects; see, e.g., Layzer & Hively (1973), Wright (1982), Wollman (1992), and Aguirre (2000) on “cold big bang” models, or Wickramasinghe et al. (1975) and Hoyle & Wickramasinghe (1988) on steady state models. In cold big bang models, thermalization takes place at very high $z$ after energy emission by Population III objects. Both cosmologies require grains of a type that can maintain a temperature very close to that of the CMB.

If the grains have a temperature only slightly different from that of the CMB, they will be too cool to contribute to the FIRB; however, spectral distortions of an initially blackbody CMB will occur (e.g., Rowan-Robinson, Negroponte, & Silk 1979; Hawkins & Wright 1988; Bond et al. 1991). More recently, this effect has been used by Loeb & Haiman (1997) and Ferrara et al. (1999) to limit the density of IG dust. We perform a similar analysis using the method and assumptions outlined in §3, and with the dust model described in §2.

Models that distort the CMB at long ($\gtrsim 1$ mm) wavelengths can be easily constrained, since there is a clear model for the CMB (perfect blackbody). But in the absence of an equally unique and well-defined model for the FIRB, it is much less clear how to limit FIR emission that does not actually exceed the observed FIR background. The procedure adopted here is as follows: following the methodology of Fixsen et al. (1996), we fit the results from 500–5000 μm by a blackbody $B_\lambda(T_{\text{CMB}})$ plus a “uniform dust component” parameterized by an emissivity and temperature in a $v^2 B_\lambda(T)$ spectrum. These fitted components are shown by dotted lines in Figure 1. The spectrum with the CMB only subtracted is shown as a solid line; this makes clear the contribution of IG dust emission to the FIRB. The residuals with both components subtracted are shown in the second panel, along with the FIRAS frequency range (Fig. 1, vertical dotted lines) and the limit on rms deviations from blackbody (horizontal dotted line).

An interesting note about this general procedure is that our calculations show that the fitted CMB temperature may be close to, but not exactly the same as the actual initial CMB, and this small discrepancy affects the measured slope of the FIR emission at $\lambda \gtrsim 850$ μm, since the FIRB is $\lesssim 1/1000$ of the CMB flux there. For example, fitting the CMB plus $v^2 B_\lambda$ gives a fitted CMB temperature of 2.72800 K, exactly as it should be. But if we fit a CMB plus $v^{0.64} B_\lambda$ (the shape of the FIRAS fit), we find $T_{\text{CMB}} = 2.72795$ K. The CMB is then slightly undersubtracted, and the residual FIRB closely follows a $I_\lambda \propto v^{0.64}$ shape at long $\lambda$. This suggests that accurately determining the slope of the FIRB long-wavelength tail requires knowledge of $T_{\text{CMB}}$ to much higher accuracy than available from COBE data. For this reason, we find that it is not useful to compare the FIRB slope predicted by models to the FIRAS fit for $\lambda \gtrsim 850$ μm.

Table 1 gives the rms deviation from blackbody for the computed spectra, with the mean taken over the 500 ≤ $\lambda$ ≤ 5000 μm wavelength range analyzed by Fixsen et al. (1996) and divided by the peak of $B_\lambda(T_{\text{CMB}})$. The limit given by Fixsen et al. (1996) on this number is $5 \times 10^{-5}$. The result of this analysis is that the dust emission would not cause detectable distortions to the CMB for the dust model described, despite the fact that the amount of emission
appears to violate the quoted limits on the $\gamma$-parameter.\(^3\)

The residuals are, of course, even smaller if the “uniform dust component” is fitted using a free index in the power law.

On the other hand, modification of the long-wavelength opacity of the dust can be important, since dust types with higher FIR opacity have lower equilibrium temperatures, which may lead to excessive emission in the FIRB/CMB. Since the dust emission tends to be well described by the fitted $v^2B_\lambda$ isotropic dust component, this emission does not tend to leave excessive distortion in the CMB residuals. Rather, it leads to a fit of the isotropic dust component incompatible with that found by FIRAS. Accordingly, we discuss these models in the next section, which treats the dust contribution to the FIRB and the resulting limits on the dust models.

5. IG DUST CONTRIBUTION TO THE FIRB

In this section, we analyze the contribution by IG dust emission to the FIRB in a variety of models. Section 5.1 presents and discusses our fiducial model. Section 5.2 lists possible variations in the parameters and discusses the effects of these variations, and § 5.3 discusses how resolution of the FIRB into discrete sources by future experiments would improve the constraints.

5.1. Fiducial Model

In our fiducial model, the cosmology is open, with $\Omega = 0.2$ and $h_{100} = 1$. The star formation rate is taken from M99 and shown in A99, Figure 1. The dust has equal parts by mass in silicate and graphite grains with $a_{\text{min}} = 0.1$ $\mu$m, and density proportional to the integrated SFR, normalized to $\Omega_{\text{gas}}(z = 0) = 5.4 \times 10^{-5}$, which gives 0.15 mag of extinction to $z = 0.5$ at (observed) 0.66 $\mu$m. The galaxy spectrum is a 9000 K blackbody, normalized to give 20 nW m$^{-2}$ sr$^{-1}$ after dust processing at 0.55 $\mu$m.

The predictions of the fiducial model appear in Figure 1 and Table 1. The figure shows the complete final spectrum with the CMB (fitted using the method of § 4) subtracted. For comparison, we also include the UVB lower limits (Pozzetti et al. 1998) and detections (Bernstein 1997), the DIRBE FIRB upper limits and detections (Hauser et al. 1998), and the FIRAS detections (Fixsen et al. 1998) with $\pm 1$ $\sigma$ uncertainties. It is apparent that the dust emission contributes significantly to the long-wavelength flux (in fact, it can account for all of the 850 $\mu$m flux given by the FIRAS measurements), but fails to reproduce the shape or amplitude of the entire FIRB. This is specified quantitatively in Table 1, where columns (5) and (6) list the numerical fraction of the FIRAS FIRB measurements that the dust emission would contribute at 200 and 850 $\mu$m. These numbers should be multiplied by 0.76 to yield the fraction of the 1 $\sigma$ upper limit on the FIRB, or 1.25 to account for the minimum 20% resolved fraction. Column (7) lists the $\gamma$-parameter represented by the FIR emission, defined by $\gamma \equiv 0.25(u_{\text{tot}}/u_{\text{CMB}} - 1)$, where $u_{\text{tot}}$ and $u_{\text{CMB}}$ are the total energy density and the energy density of the CMB alone, both evaluated in the 60–600 GHz frequency range. This gives a measure of the total dust energy output. The last column gives the rms residual after both CMB and the $v^2B_\lambda$ fit to the FIR emission are subtracted, as discussed in § 4.

The next section analyzes the possible variations upon these predictions resulting from changes in the model. Some of the variations can be ruled out because they predict a FIRB contribution above the FIRAS limit; these models could be saved only if the FIRAS team has oversubtracted the foreground contribution. Stronger limits can be obtained on the various models by considering their contribution to the unresolved fraction of the FIRB, after the

| Model     | Variation | $T_{\text{Gr}}$ | $T_{\text{in}}$ | $f_{200}$ | $f_{850}$ | $y_{\text{FIRB}}/10^{-4}$ | rms/10$^{-4}$ |
|-----------|-----------|-----------------|-----------------|-----------|-----------|--------------------------|---------------|
| Fiducial  | ...       | 9.9             | 7.3             | 0.14      | 1.02      | 2.0                      | 3.7           |
| H80       | $H_0 = 80$ $\text{km s}^{-1} \text{Mpc}^{-1}$ | 9.9             | 7.3             | 0.15      | 1.10      | 2.1                      | 4.0           |
| FSFR      | SFR flat for $z > 3$ | 9.9             | 7.3             | 0.16      | 1.45      | 2.7                      | 7.4           |
| BC        | Galaxy spectra from Bruzual-Charlot | 9.3             | 7.8             | 0.08      | 0.89      | 1.7                      | 2.9           |
| BC2       | Bruzual-Charlot + extreme reddening | 10.5            | 7.9             | 0.24      | 1.26      | 2.5                      | 4.6           |
| MG        | $a = 0.1$ $\mu$m grains, $\Omega_{\text{dust}} = 4.5 \times 10^{-9}$ | 10.2            | 7.1             | 0.17      | 0.96      | 1.9                      | 3.4           |
| LG        | $a = 0.25$ $\mu$m grains, $\Omega_{\text{dust}} = 7.6 \times 10^{-5}$ | 9.2             | 7.4             | 0.08      | 0.85      | 1.6                      | 3.1           |
| LUV       | UVB of 10 nW m$^{-2}$ sr$^{-1}$ at 0.55 $\mu$m | 8.8             | 6.5             | 0.05      | 0.72      | 1.3                      | 2.5           |
| SCDM      | $\Omega = 1$, $\Omega_{\text{dust}} = 1.25 \times 10^{-4}$ | 9.9             | 7.3             | 0.30      | 1.94      | 3.8                      | 6.7           |
| SCDMb     | SCDM, but UVB of 10 nW m$^{-2}$ sr$^{-1}$ | 8.8             | 6.5             | 0.10      | 1.33      | 2.5                      | 4.4           |
| G05       | $\kappa$ flat to $\lambda_0 = 0.5$ $\mu$m | 17.3            | 11.3            | 0.86      | 0.45      | 1.1                      | 1.1           |
| G2        | $\kappa$ flat to $\lambda_0 = 2$ $\mu$m | 12.8            | 11.3            | 0.88      | 1.56      | 3.5                      | 4.6           |
| G5        | $\kappa$ flat to $\lambda_0 = 5$ $\mu$m | 9.7             | 9.3             | 0.53      | 3.97      | 7.8                      | 12            |
| G10       | $\kappa$ flat to $\lambda_0 = 10$ $\mu$m | 7.7             | 6.5             | 0.24      | 7.71      | 13.4                     | 19            |
| L1.0      | $\kappa(\lambda \geq 100 \mu$m) $\propto \lambda^{-1}$ | 7.9             | 5.5             | 0.038     | 2.59      | 4.4                      | 18            |
| L1.5      | $\kappa(\lambda \geq 100 \mu$m) $\propto \lambda^{-1.5}$ | 9.0             | 6.4             | 0.083     | 1.71      | 3.1                      | 9.5           |
| L2.5      | $\kappa(\lambda \geq 100 \mu$m) $\propto \lambda^{-2.5}$ | 10.6            | 8.0             | 0.19      | 0.65      | 1.3                      | 1.7           |
| GRA       | Graphite, $a_{\text{min}} = 0.05$ $\mu$m | 9.8             | 9.3             | 0.21      | 1.29      | 2.6                      | 4.4           |
| S2        | 1:2 graphite:silicate by mass | 9.9             | 7.3             | 0.12      | 1.00      | 1.9                      | 3.7           |

\(^3\) In light of the uncertainty in the FIRB, it seems that the quoted limits on rms distortions and the $\gamma$-parameter from the COBE group must be used with caution. Rather large spectral distortions can be “hidden” in the microwave tail of the FIRB, which has a poorly defined spectral shape. Assuming conservatively that the FIRB as detected by FIRAS exists in the 150–600 GHz range (and zero outside), it corresponds to a $\gamma$-parameter in the full 60–600 GHz interval of $2 \times 10^{-4}$, over an order of magnitude above the quoted upper limit.
concerns single-temperature blackbody galaxy spectrum, to find a more realistic spectral template. We utilize the Bruzual-Charlot (in preparation) starburst population synthesis model with a Scalo IMF to compute the shape of the spectrum as a function of the age of the population. This time-dependent template is convolved with the SFR from M99 to find the redshift evolution of the frequency-dependent UV emissivity. The full spectrum under these assumptions is shown by the curve labeled “BC” in Figure 2. The peak in the UVB from the direct galactic emission is broader than in our fiducial model, and extends to higher energies. As mentioned above, this procedure results in a UVB at z = 0 that falls short of the measured value by a factor of ~2. Overall, the contribution to the FIRB is not significantly affected: it is reduced by only ~10% relative to our fiducial model at 850 µm (see Table 1).

It must be noted that the above procedure is not strictly correct, since we have not corrected the galactic templates for reddening by dust internal to the galaxy. This reddening could be important in the present context, since it makes the UV peak steeper in the 0.1–1 µm range, and allows a broader UVB in this wavelength range that reaches ~20 nW m⁻² sr⁻¹ at 0.55 µm, while extending to energies higher than assumed in our fiducial model. Here we do not attempt to derive an accurate reddening correction (see instead Madau et al. 1998). Rather, our aim is to assess the maximum UV flux that could, in principle, be present in the 0.1–1 µm range, and that is consistent with both the Voyager upper limit (Murthy, Henry, & Holberg 1998) and the 0.55 µm detection.

To compute this maximal UV flux, we reddened the galactic template spectrum, assuming the cross section of Milky Way dust (DL), with a total (unrealistically high) maximum optical depth of ~4. We then rescaled the UV efficiency by a factor of ~10 to retain an intensity of ~20 nW m⁻² sr⁻¹ at 0.55 µm. The resulting spectrum is shown by the curve labeled “BC2” in Figure 2. This spectrum fits in with both the Voyager and Bernstein (1997) data points, and reasonably represents the maximally allowed UV emission. It is interesting to note that a simultaneous fit to these two data points requires a very steep spectrum (20 nW m⁻² sr⁻¹ at 0.55 µm to 0.6 nW m⁻² sr⁻¹ at 0.1 µm, implying a slope of I ~ z²), which can only be derived from the Bruzual-Charlot template by postulating an exceedingly high reddening. One resolution of this paradox might be that the true value of the UVB is closer to 10 nW m⁻² sr⁻¹ (as argued by Vogeley 1997 in a different context). We find that with this maximal emission, the FIRB contribution increases somewhat, but the change is once again not significant, only ~40% relative to the galactic model without reddening, overpredicting the 850 µm FIRB by ~26% (cf. Table 1), but still well within the +1σ uncertainty.

Finally, we check our assumption that the dust temperature follows from equilibrium with a homogeneous background radiation bath, because dust near concentrations of radiation could have somewhat higher temperatures. To determine whether this might be important, we have computed the critical distance, r_{crit}(z) (from center of a model galaxy), at which a dust grain would feel equal contributions from the cosmic UVB intensity, νJ(ν), and from the nearby galaxy, i.e.

\[ 4π(1 + z)^3νJν = \frac{L_{gal}}{4πr_{crit}^2}, \]

where the galaxy luminosity L_{gal} ~ 10^{46} ergs⁻¹ (corresponding to a 10^{12} M☉ starburst galaxy, with the spectral model of G. Bruzual & S. Charlot in preparation) is constant and νJ(ν) is proportional to the integrated comoving SFR and has the value of 20 nW m⁻² sr⁻¹ at z = 0. The result is that r_{crit} ~ 60 kpc for all z and r_{crit} ~ 30 kpc for z > 1. In A99, it was argued that IG dust must be ≥70 kpc from its progenitor galaxy to be uniform enough to be in accord with limits on the dispersion in supernova brightnesses. Thus, even near extremely bright galaxies, dust of the A99 model should have temperatures dominated by the isotropic background rather than nearby galaxies.

As discussed in § 3, there are still sizeable uncertainties in the normalization of the UV spectrum. The 1σ lower limits from Bernstein (1997) roughly coincide with the lower limits given by integrated counts (M99) at ~10 nW m⁻² sr⁻¹ at 0.55 µm. We have employed this normalization (model LUV), and find that this lowers the 850 µm flux by about 30% (the decrease in energy is somewhat offset by the lower temperature of the dust).

Although most models considered predict an 850 µm flux comparable to that detected by FIRAS, some models exceed the FIRAS upper limit. To reconcile the supernova measurements with a closed, matter-dominated cosmology (such as the standard cold dark matter model [SCDM]), an extinction of A_V(z ~ 0.5) ~ 0.35 mag is required (A99), in turn requiring \( r_{crit}(z = 0) \approx 1.25 \times 10^{-4} \) for \( h_{50} = 1 \). In the present model, this predicts an 850 µm flux, which exceeds...
the 1 σ bound of the FIRAS detection (see the SCDM model in Table 1.) With the lower UV normalization, however, the emission is marginally compatible with the errors (model SCDMb in Table 1). If the higher UV normalization holds, these results make it very unlikely that IG dust could reconcile SCDM with the supernova observations, even if the large necessary quantity of dust existed (cf. A99).

The present calculations can also constrain the properties of intergalactic dust if it is assumed to be responsible for the supernova dimming. Very gray dust, for instance, absorbs more UV/optical flux for a given V-band extinction (and can hence overproduce the FIRB). Both very gray dust and “standard” dust with high IR emissivity can also have a lower equilibrium temperature, which overproduces the FIRB at long wavelengths. To limit these sorts of dust, we have considered two illustrative types. The first is dust that is gray out to some wavelength \( \lambda_0 \), then falls as \( \lambda^{-2} \),

\[
\kappa_\lambda \propto \frac{1}{[1 + (\lambda/\lambda_0)^2]} .
\]  

(11)

This is conservative in the sense of ensuring the maximum reasonable temperature for a given \( \lambda_0 \). Models G05–G10 are of this type and show that for \( \lambda_0 \gtrsim 3 \mu m \) the FIRB is overproduced. It is interesting to note, however, that \( \lambda_0 \approx 0.5 \mu m \) models actually produce a FIRB fitting the observations rather well over the entire frequency range. Conducting needles have an absorption spectrum that can be roughly modeled by equation (11) (Wright 1982; Wickramasinghe & Wallis 1996; Aguirre 1999a), and using Wright’s (1982) RC model with a resistivity of \( \sim 10^{-15} \) s, we can rule out needle models with length-to-diameter ratios \( L/d \gtrsim 6 \).

The second dust type is “standard” DL/MRN dust, but with long-wavelength (\( \lambda \gtrsim 100 \mu m \)) emissivity given by \( \kappa_\lambda \propto \lambda^{-\alpha} \) with \( \alpha \neq 2 \). Fluffy/fractal grains can give \( \alpha \sim 1 \) (e.g., Wright 1987; Stognienko, Henning, & Ossenkopf 1995), and \( \alpha \) generally depends upon the optical properties of the grain material. Dust with \( \alpha < 2 \) generally has a lower temperature, and the calculations (see models L1.0 and L1.5 in Table 1) show that such dust will overproduce the 850 \( \mu m \) FIRB (at the 1 σ level) for \( \alpha \gtrsim 1.5 \). On the other hand, if the dust had \( \alpha > 2 \), model L2.5 shows that the higher resulting temperature would lead to less flux at 850 \( \mu m \). The comoving dust temperature, \( T_{\text{dust}}/(1+z) \), for the fiducial model and models GR05 and L1.0 is shown in Figure 3. All computed models fall within the range spanned by the GR05 and L1.0 models.

In summary, using only the FIRAS limits on the FIRB, we can with some confidence rule out SCDM models, “very gray” dust models with \( \lambda_0 \gtrsim 3 \mu m \), and dust models with power-law index \( \lesssim 1.5 \) in their long-wavelength emissivity. The next section discusses stronger constraints that derive from the fraction of the measured FIRB known to be due to discrete sources.

5.3. Resolving the FIRB: Tests and Future Observations

When constraining models using their predicted IG dust contribution to the FIRB, we have so far considered the full

---

Footnote: Needles with high \( L/d \) and high conductivity, such as the iron whiskers of Hoyle & Wickramasinghe (1988), can maintain a temperature very close to that of the CMB and are not constrained by the present calculations; see also Aguirre (2000).
massive constraints on the models. It must also be noted, resolving the FIRB further could provide significantly more FIRB intensity range at \( z \approx 2 \). For comparison, Guiderdoni et al. (1997) give an allowed uncertainty, reflecting only differences between the fits to the data. The calculated error on the resolved fraction, column (6) should be multiplied by 0.95. The calculations therefore indicate that the source fluxes are derived using a 30' aperture, which at \( z > 1 \) corresponds to a physical size of \( \approx 250 \ h_0^{-1} \) kpc. We have assumed for simplicity that the IG dust is effectively uniform, but at \( z > 1 \) significant quantities could be within 125 kpc of galaxies, so there is a danger that the SCUBA-derived fluxes include some emission from what we have termed IG dust. Coming submillimeter surveys with better angular resolution should be able to clarify this ambiguity.

In summary, with a factor of 4 improvement over the current SCUBA detection threshold, we would either see explicitly the need for something else to explain the FIRB, or else a fairly tight constraint on the IG dust will be possible. Forthcoming instruments such BOLOCAM and the Space Infrared Telescope Facility (SIRTF) will reach the required sensitivities at 160 and 1100 \( \mu m \) (see Table 1 of Blain 1999). The constraints obtained might then be limited by the accuracy of the absolute measurement of the coarse-grained FIRB. The High Frequency Instrument (HFI) on the future Planck satellite, covering the 350–3000 \( \mu m \) range at several intermediate frequencies, will be able to greatly improve our existing knowledge of the unresolved component. Finally, as shown by Haiman & Knox (1999), angular correlations in the FIRB are expected to be at the few percent level, and depend strongly on the nature of its sources. Future instruments such as BLAZE and FIRBAT will be able to measure these correlations, providing another diagnostic that distinguishes between IG dust and discrete sources.

6. CONCLUSIONS

In this paper, we studied the far-infrared emission from the type and amount of IG dust necessary to explain the recent Hubble diagrams, derived from observations of Type Ia SNe at redshifts \( 0 < z < 1 \), in cosmological models without a cosmological constant. In particular, we computed the contribution from the IG dust emission to the value of the FIRB recently measured by the COBE satellite.

---

5 See http://astro.estec.esa.nl/SA-general/Projects/Planck.
We investigated a broad range of models, and focused on the wavelength of 850 \( \mu m \), where the largest fraction of the FIRB is presently resolved into discrete sources, thus yielding the strongest constraints. The current constraints are limited by \(~10\%\)–\(30\\)% errors each in the dust model, the measured FIRB flux, the SCUBA counts, and the SCUBA calibration.

Our results show that the IG dust emission is consistent with the spectral distortion of the CMB allowed by present COBE data, but may contribute nearly all of the unresolved fraction of the FIRB in the 300–1000 \( \mu m \) range. In a few specific models, this contribution is sufficiently large to render those models implausible, including standard CDM and models with very gray dust or dust with unusually high IR emissivity. In the (perhaps most interesting) case of an open universe with a low matter density (\( \Omega = 0.2 \)), we find that the contribution is still within the experimental uncertainty. Assuming that 20\% of the FIRB is accounted for by the discrete SCUBA sources, the IG dust contributes up to \(~90\\)% of the \(+1\sigma\) limit on the unresolved fraction. Future observations of the far-infrared background by Planck, and its discrete constituents by SIRTF and BOLOCAM, will provide a definitive test of the IG dust hypothesis.

We thank I. Smail, R. Ivison, and D. Fixsen for helpful communications, and P. Madau for providing a fitting formula for the SFR. Z. H. was supported by the Department of Energy and NASA grant NAG5-7092 at Fermilab. This work was supported in part by the National Science Foundation grant PHY-9507695.

REFERENCES

Aguirre, A. 1999a, ApJ, 512, L19
———. 1999b, ApJ, 525, 583 (A99)
———. 2000, ApJ, submitted
Barger, A. J., Cowie, L. L., & Sanders, D. B. 1999a, ApJL, in press (preprint astro-ph/9904126)
Barger, A. J., Cowie, L. L., Smail, I., Ivison, R. J., Blain, A. W., & Kneib, J.-P. 1999b, AJ, in press (preprint astro-ph/9903142)
Bernstein, R. 1997, Ph.D. thesis, Caltech
Blain, A. W. 1999, in Proc. Photometric Redshift Meeting, OCIW (preprint astro-ph/9906141)
Blain, A. W., Ivison, R., Kneib, J.-P., & Smail, I. 1999a, preprint (astro-ph/9908024)
Blain, A. W., Kneib, J.-P., Ivison, R. J., & Smail, I. 1999b, ApJ, 512, L87
Bond, J. R., Carr, B. J., & Hogan, C. J. 1991, ApJ, 367, 420
Draine, B., & Lee, H. 1984, ApJ, 285, 89 (DL)
Eisenstein, D. J. 1997, ApJ, submitted (preprint astro-ph/9709054)
Ferrara, A., Nath, B., Sethi, S. K., & Shchekinov, Y. 1999, MNRAS, 303, 301
Fixsen, D. J., Cheng, E. S., Gales, J. M., Mather, J. C., Shafer, R. A., & Wright, E. L. 1996, ApJ, 473, 576
Fixsen, D. J., Dwek, E., Mather, J. C., Bennett, C. L., & Shafer, R. A. 1998, ApJ, 508, 123
Gehrz, R. D. 1989, in IAU Symp. 135, Interstellar Dust, ed. L. J. Allamandola & A. G. G. M. Tielens (Dordrecht: Kluwer), 445
Guiderdoni, B., Bouchet, F. R., Puget, J.-L., Lagache, G., & Hivon, E. 1997, Nature, 390, 257
Guiderdoni, B., Hivon, E., Bouchet, F. R., & Maffei, B. 1998, MNRAS, 295, 877
Haiman, Z., & Knox, L. 1999, ApJL, submitted (preprint astro-ph/9906399)
Haiman, Z., & Loeb, A. 1998, ApJ, 503, 505
Hauser, M. G., et al. 1998, ApJ, 508, 25
Hawkins, I., & Wright, E. 1988, ApJ, 324, 46
Hoye, F., & Wickramasinghe, N. 1988, ApSS, 147, 245
Hughes, D. H., et al. 1998, Nature, 394, 241
Laor, A., & Draine, B. 1993, ApJ, 402, 441
Layzer, D., & Hively, R. 1973, ApJ, 179, 361
Loeb, A., & Haiman, Z. 1997, ApJ, 490, 571
Madau, P. 1999, Phys. Scr., in press (preprint astro-ph/9902228) (M99)
Madau, P., Pozzetti, L., & Dickinson, M. 1998, ApJ, 498, 106
Mathis, J., Rumpl, W., & Nordsieck, K. 1977, ApJ, 217, 425 (MRN)
Murthy, J., Henry, R. C., & Holberg, J. B. 1998, BAAS, 193, 6509
Pei, Y., Fall, M., & Hauser, M. 1999, ApJ, 522, 604
Perlmutter, S., et al. 1999, ApJ, 517, 565
Pozzetti, L., Madau, P., Zamorani, G., Ferguson, H. C., & Bruzual A. G. 1998, MNRAS, 298, 1133
Puget, J.-L., Abergel, A., Bernard, J.-P., Boulanger, F., Burton, W. B., Desert, F.-X., & Hartmann, D. 1996, A&A, 308, L5
Renzini, A. 1997, ApJ, 488, 35
Riess, A. G., et al. 1998, AJ, 116, 1009
Rowan-Robinson, M., Negroponte, J., & Silk, J. 1979, Nature, 281, 635
Stognienko, R., Henning, Th., & Ossenkopf, V. 1995, A&A, 296, 797
Voigley, M. 1997, ApJ, submitted (preprint astro-ph/9711209)
Weingartner, J., & Draine, B. T. 1999, preprint (astro-ph/9907251)
Wickramasinghe, N. C., & Wallis, D. H. 1996, ApSS, 240, 157
Wollman, E. 1992, ApJ, 392, 80
Wright, E. L. 1981, ApJ, 250, 1
———. 1982, ApJ, 255, 401
———. 1987, ApJ, 320, 818