Notes on Intergalactic Dust E.D. Commins January, 2002

8. <u>The Problem of Intergalactic Dust: general remarks</u>

In Sec. 3 we briefly mentioned Aguirre's suggestion that dimming of light from distant SN1a might arise from extinction due to intergalactic (IG) dust, rather than from acceleration of the Hubble expansion. Here we want to investigate this question in some detail. Our goal is to determine whether practical observations, already completed or possible in the relatively near future, can place limits on the extinction due to IG dust. It is important to remind ourselves at the outset that there is at present no incontrovertible evidence for IG dust, but only crude upper limits on its absorption coefficient.

In order to establish quantitative criteria, we follow the path laid out by [Aguirre,1999a,b] and by Aguirre and Haiman [Aguirre 2000]. However, before we go into details, let's sketch their main ideas very roughly, as follows. If we go back in time to sufficiently large z (let us say $z \approx 20$ for the sake of discussion) it is generally believed that there was little or no dust. It is assumed that dust was created in galaxies, particularly during intense periods of star formation, and that the bulk of this occurred since z=20. Aguirre assumes that a portion of the galactic dust was then driven out of galaxies by radiation pressure. The grains with the largest opacities were most susceptible to this pressure: these are the long needle-like grains which have absorption coefficients relatively independent of wavelength ("gray" opacity). The large grains are also least susceptible to destruction by various mechanisms such as sputtering. Crude but at least superficially plausible estimates by Aguirre suggest that the radiation pressure might have been sufficient to fill the space between galaxies more or less uniformly with IG dust in a relatively short time ($\approx 10^9$ years).

If such IG dust exists it must absorb starlight in the UV and visible, and re-radiate it in the IR. Let's assume that we can determine a global luminosity function for stars as a function of z, in the UV and visible. We also assume that in any given small volume, the dust is in local thermodynamic equilibrium (LTE) with all the radiation arising from the starlight, from the cosmic microwave background (CMB), and from other dust. Then, by solving the equation of radiative transport we can in principle work out the modified radiation flux observed by us at z=0. Of course this radiation flux depends on several factors, most importantly the dust absorption coefficient versus wavelength, the global star formation rate (SFR), and an assumed relationship between the SFR and the dust density. There are also several important constraints on the calculated radiation flux:

a) The diffuse background flux in the visible (550 nm) is approximately 20 nW m^{-1} sr^{-1}.

b) There exists a diffuse far-infrared background (DFIRB), knowledge of which comes from FIRAS-COBE observations in the wavelength range 140-1000 microns. There also exist observations of discrete FIR sources at 850 microns by SCUBA at the J. C. Maxwell telescope. Indeed, the mean value of the DFIRB at 850 μ actually agrees with the value of the flux obtained by SCUBA, suggesting that all of the DFIRB might be accounted for by faint discrete sources. However, there is a relatively large uncertainty in each measurement, which leaves room for a possible contribution by IG dust. In fact, the latter could be as large as 0.6 nW m^{-2} sr^{-1} at 850 microns.

c) Various astrophysical arguments involving the production of "metals" in stars suggest that the intergalactic dust density could not be larger than a certain upper limit, characterized by the inequality: $\Omega_{\Delta\upsilon\sigma\tau}(z=0) \le (1\text{–}2)\bullet 10^{-4}$.
d) Existing observations of color excesses in SN1a light as a function of z can be used to impose limits on the wavelength dependence of I.G. dust -induced extinction. From [Perlmutter 1999] we shall assume that the data give $E_{\text{Rest frame}}(B\text{-}V) \le 0.04$ at $z \approx 0.5$.

8. The Radiation Transport Calculation

We have constructed a code: Dust Evolution.F, in order to verify and extend the calculations of Aguirre and Haiman, and to investigate quantitatively the issues raised in the previous section. Our calculation makes use of the following quantities and relations:

8.1 The co-moving photon density per octave N(ν):

$$N(\nu) = \frac{4\pi}{hc(1+z)^3} J_{\nu(1+z)}(z) \qquad \text{in cm}^{-3} \tag{32}$$

where h = Planck's constant = $6.625\bullet 10^{-27}$ erg-s, c = velocity of light = $2.9979\bullet 10^{10}$ cm/s, z is the red-shift, and $J_{\nu(1+z)}(z)$ is the *specific* radiation flux in erg cm^{-2} s^{-1} Hz^{-1} sr^{-1}. If we go back to a sufficiently early time (let us say z=20), N(ν) becomes an initial function $N_0(\nu)$. Apart from a factor of h, the latter is just the Planck energy density per Hz for the CMB:

$$N_0(\nu) = \frac{8\pi\nu^3}{c^3} \frac{1}{\exp\left(\frac{h\nu}{kT_0}\right) - 1} \tag{33}$$

where T_0 =2.728 K is the present CMB temperature. We shall see that N(ν) has convenient properties for calculation.

8.2 The global star formation rate $\dot{\rho}_*$

It has been realized for some years now that the global star formation rate (SFR) was approximately 5 to 10 times greater at z=1 than it is now. There is very large uncertainty (one should better say almost total ignorance) about what the SFR was for z>3 or so. Here we shall simply assume that the SFR is obtained from a fit to the data from various investigators, as shown for example in Nagamine, Cen and Ostriker [Nagamine 2000]. We thus obtain the following expression for the SFR:

$$\dot{\rho}_* = 6.81\bullet 10^{-50}(1+10.23z)e^{-.503z} \quad \text{g s}^{-1} cm^{-3} \tag{34}$$

where the coefficients in this expression all have very large uncertainty.

8.3 The relation between dust density and SFR:
Here we assume that:

$$\Omega_{Dust}(z) = A\int_{t(z=20)}^{t(z)} \dot{\rho}_*(z)dt \tag{35}$$

where A is a constant to be determined. Eq. 35 expresses the basic assumption that the rate of production of IG dust is proportional to the global star formation rate.

From Friedmann's equations we have the fundamental relation:

$$\frac{dt}{dz} = -\frac{1}{H_0}\frac{1}{(1+z)^2\left[1+z\Omega_m + \left(\frac{1}{(1+z)^2}-1\right)\Omega_\Lambda\right]^{1/2}} \tag{36}$$

where H_0=Hubble's constant (assumed in these calculations to be 65 km s^{-1} Mpc^{-1}). For $\Omega_\Lambda=0$, $\Omega_m=1$, eq. 36 reduces to:

$$\frac{dt}{dz} = -\frac{1}{H_0}\frac{1}{(1+z)^{5/2}} \tag{37}$$

and eq. 35 then becomes:

$$\Omega_{Dust}(z) = const \bullet \int_z^{20} \frac{(1+10.23z')\exp(-.503z')}{(1+z')^{5/2}}dz' \tag{38}$$

Numerical evaluation of this integral for a wide range of z values shows that to a very good approximation:

$$\Omega_{Dust}(z) = \Omega_{Dust}(0)\exp(-0.80z) \tag{39}$$

The co-moving dust density is then:

$$\rho_{Dust}(z) = (1+z)^3\Omega_{Dust}(z)\rho_0 \tag{40}$$

where

$$\rho_0 = \frac{3H_0^2}{8\pi G} = 8.2 \bullet 10^{-30} \text{ g cm}^{-3} \tag{41}$$

Thus (40) becomes:

$$\rho_{Dust}(z) = \Omega_{Dust}(0) \bullet 8.2 \bullet 10^{-30}(1+z)^3 e^{-0.8z} \tag{42}$$

Fig. 20 shows how the co-moving dust density varies with z according to (42).

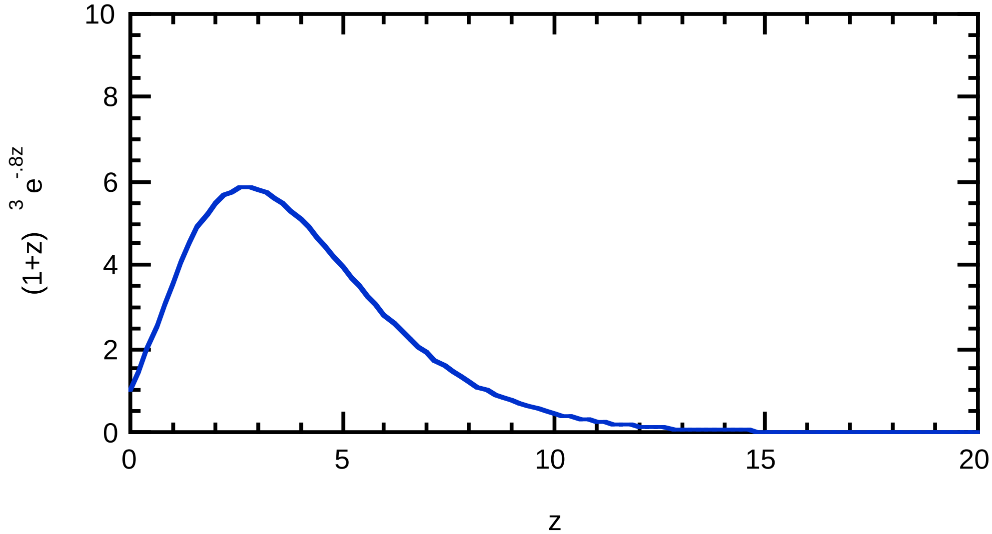

Fig. 20 Variation of the co-moving dust density with z. The maximum occurs at z≈3.

8.4 <u>The IG dust absorption coefficient:</u>

The absorption coefficient is:

$$\alpha_\nu(z) = \rho_{Dust}(z) \bullet \kappa_{\nu(1+z)}(z) \tag{43}$$

where κ_ν is the opacity in cm^2 g^{-1}. Once $\alpha_\nu(z)$ is found we can calculate the optical depth to z at frequency ν (corresponding wavelength λ) from the formula:

$$\tau_\lambda(z) = \frac{c}{H_0}\int_0^z \frac{\alpha_\lambda(z)dz}{(1+z)^2\sqrt{1+\Omega_m z + \left(\frac{1}{(1+z)^2}-1\right)\Omega_\Lambda}} \tag{44}$$

and then obtain the extinction from:

$$A_\lambda(z) = 1.086\tau_\lambda(z) \tag{45}$$

In particular, if we assume Ω_m=1, Ω_Λ=0, we have:

$$A_\lambda(z) = 1.086\frac{c}{H_0}\int_0^z \frac{\alpha_\nu(x)dx}{(1+x)^{5/2}} \tag{46}$$

What is the magnitude of κ_ν and how does it depend on wavelength? One finds that for a wide range of dust grain compositions and sizes, κ_ν(z=0) is about 10^5 cm^2 g^{-1} at x=10 μ^{-1}, within about a factor of 2 or so. In Fig.21 we sketch 8 different hypothetical opacities (Models I.G. 1-8) as a function of x, assuming that each takes the value $1.2 \bullet 10^5$ at x=10. Curves 1-4 represent 4 different “standard galactic opacities” for R_V = 2, 4, 6, and 8 respectively, as parameterized by Cardelli, Clayton, and Mathis [Cardelli 1989] and analyzed physically by Draine and Lee [Draine 1984] and other authors; (see Sec. 1 of these notes). Curves 5-8 represent the functional form:

$$\kappa_n(x) = \frac{1.2 \bullet 10^5}{1 + \frac{c_n}{x^2}} \text{ cm}^2 \text{ g}^{-1} \tag{47}$$

where c_5 = 1.3, c_6 = . 25, c_7 = .025, and c_8 = .0025. These functions give a simplified representation of opacities that are frequency-independent (“gray”) over relatively wide ranges of the high-frequency band.

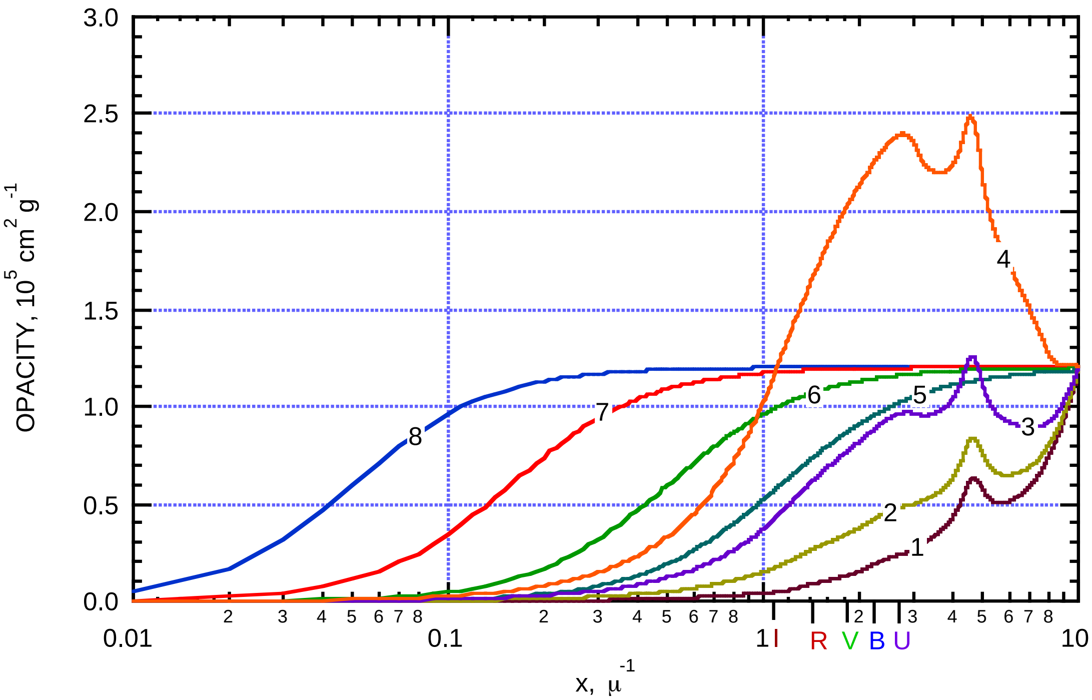

Fig. 21. Eight different opacity functions, described in text. Values of x for the standard filters U, B, V, R, I are indicated.

How can we justify our somewhat arbitrary decision to fix each of the opacities at precisely $1.2 \bullet 10^5$ at x=10? The point is that this is just a matter of convenience, because the relevant quantity in our calculations is not the opacity, but instead the absorption coefficient α, which is proportional to the dust density as well as the opacity.

8.5 <u>The equation of radiative transport. Stellar and dust emission functions.</u>

In the present application [Aguirre 2000] the differential equation of radiative transport is:

$$\frac{\partial N_\nu(z)}{\partial z} = -c\frac{\partial t}{\partial z}\left[\left(j_\nu^*(z) + j_{Dust}(z)\right) - \alpha_\nu(z) N_\nu(z)\right] \tag{49}$$

Here, j_ν^* and j_{Dust} are emission functions corresponding to starlight and dust, respectively. If these were zero, and if the absorption coefficient α_ν also vanished, N_ν would be independent of z. That is why N_ν is the convenient variable for this calculation. We shall assume that j_ν^* is given by the formula:

$$j_\nu^*(z) = A_S\,\dot{\rho}_*\,B_{\nu(1+z)}(9000\text{ K}) \tag{50}$$

Here $\dot{\rho}_*$ is the SFR (see eq. 34), and $B_{\nu(1+z)}(9000\text{ K})$ is the Planck function:

$$B_{\nu(1+z)}(9000\text{ K}) = \frac{2h\nu^3(1+z)^3}{c^2\left[\exp\left(\frac{h\nu(1+z)}{9000k}\right)-1\right]} \tag{51}$$

We choose 9000 K as an appropriate effective temperature because eq. 51 at z=0 then represents the spectral distribution of observed starlight quite well (See Fig. 22). Also A_S is a constant chosen so that the calculated flux at 550 nm and z=0 matches the observed flux.

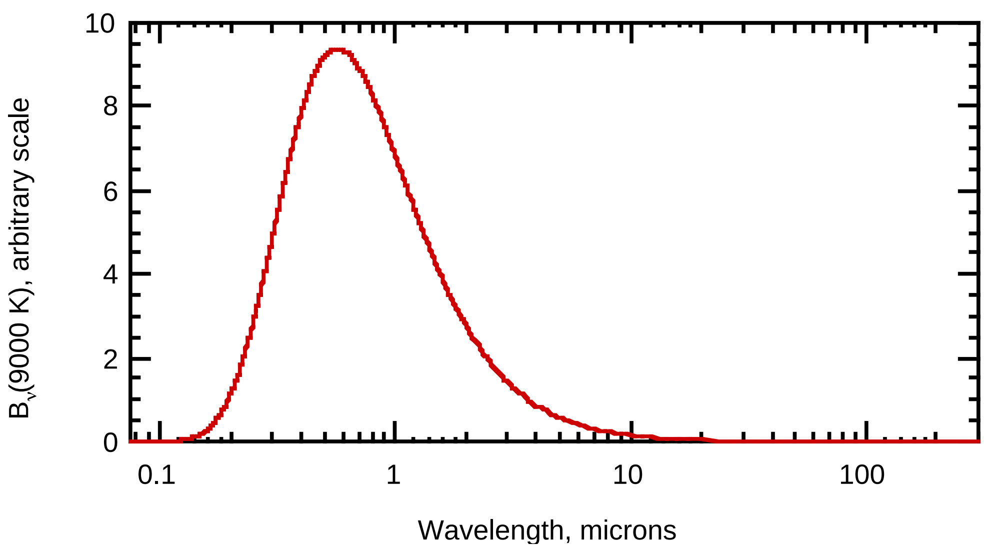

Fig. 22 The Planck function B_ν for T= 9000 K plotted versus wavelength in microns. The peak occurs at about .56 microns.

The dust emission function $j_{dust}(z)$ is given by the formula:

$$j_{Dust}(z) = \frac{8\pi\nu^3}{c^3}\frac{\alpha_\nu(z)}{\exp\left(\frac{h\nu(1+z)}{kT_D}\right)-1} \tag{52}$$

where at each z, the dust temperature is determined by imposing the condition of local thermal equilibrium:

$$\int_0^\infty \alpha_\nu N_\nu(z)d\nu = \int_0^\infty \alpha_\nu j_{Dust}(z)d\nu \qquad (53)$$

8.6 Integration of the equation of radiative transport. Output of calculation

As usual we assume that the universe is flat:

$$\Omega_m + \Omega_\Lambda = 1 \qquad (54)$$

If there were no dust and thus no extinction, the apparent magnitude at wavelength λ of a supernova at red-shift z would be given by the formula:

$$m_\lambda = M_\lambda + 5\log_{10}\left[(1+z)\int_0^z \frac{dx}{\sqrt{1+x\left(x^2+3x+3\right)\Omega_m}}\right] + C \qquad (55)$$

where M_λ is the absolute magnitude and C is a constant. Since we are trying to see whether dust rather than acceleration can account for the observed dimming of distant SN1a, we pursue the case of Ω_m=1. Then, the integral in (55) can be evaluated easily and (55) becomes:

$$m_\lambda = M_\lambda + C + 5\log_{10}\left[2(\ 1+z-\sqrt{1+z}\ )\right] \qquad (56)$$

When extinction is included, $m_\lambda \to m'_\lambda = m_\lambda + A_\lambda$. Thus (56) becomes:

$$m'_\lambda = M_\lambda + C + 5\log_{10}\left[2(1+z-\sqrt{1+z})\right] + A_\lambda \qquad (57)$$

where, as we have already shown in (46) for Ω_m=1:

$$A_\lambda = 1.086\int_0^z \frac{\alpha_\lambda(z)dz}{(1+z)^{5/2}}$$

We want to compare (57) with the corresponding apparent magnitude when there is no extinction, and Ω_m =0.28:

$$m_B = M_B + C + 5\log_{10}\left[(1+z)\int_0^z \frac{dx}{\sqrt{1+.28x\left(x^2+3x+3\right)}}\right] \qquad (58)$$

Clearly $m'_B = m_B$ when A_B takes the following “critical” value:

$$A_C = 5\log_{10}\left[\frac{\int_0^z \frac{dx}{\sqrt{1+.28x\left(x^2+3x+3\right)}}}{2\left(1-\frac{1}{\sqrt{1+z}}\right)}\right] \tag{59}$$

We plot this "critical" extinction versus z in Fig. 31:

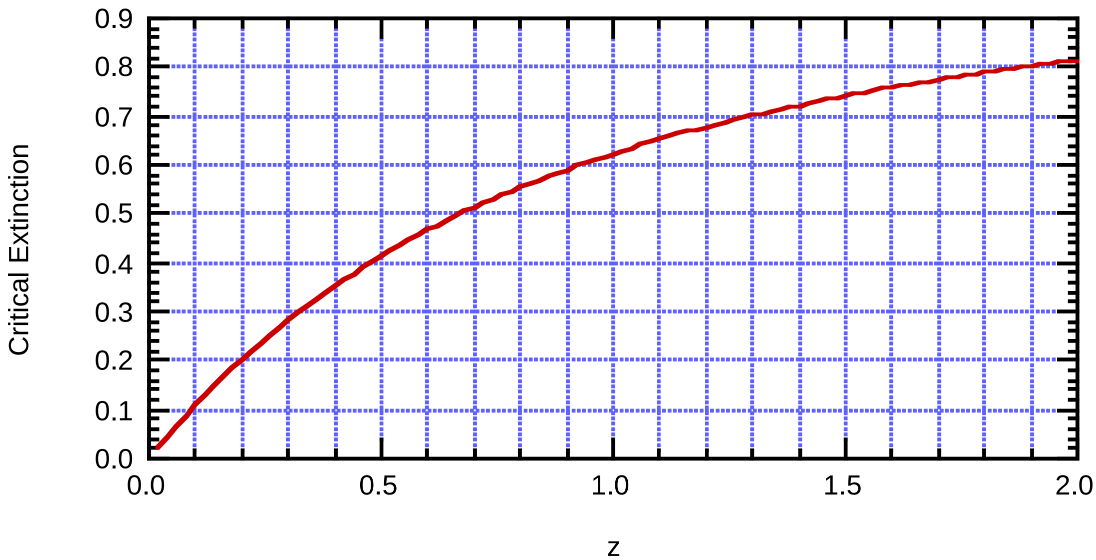

Fig. 23 Critical extinction, which causes the same dimming (for Ω_m=1) that would be observed with no extinction and Ω_m=0.28.

In any given opacity model, once we choose a value for $\Omega_{Dust}(0)$, the co-moving dust density is determined from (42), thus the absorption coefficient is fixed from (43), and hence the extinction is determined from (45) or (46). However, to determine an appropriate $\Omega_{Dust}(0)$ we must integrate the equation of radiative transport. Starting at z=20, where the SFR and the dust density are by assumption negligibly small (see eqs.34, 42 and Fig. 20), we integrate (49) for each frequency. Recall that at this initial z, $N_\nu(z)$ is given by eq. 33. The integration with respect to z proceeds in 300 steps using equal increments of ln(1+z). The frequency range is

$$10^{10} \le \nu \le 3.98 \bullet 10^{15} \text{ Hz}$$

in 560 steps, with equal increments of log ν. At each z we determine the dust temperature by requiring local thermodynamic equilibrium. The final result of the calculation is:

$$N_\nu\left(z=0\right) = \frac{4\pi}{hc} J_\nu\left(z=0\right)$$

Thus we obtain $J_\nu\left(z=0\right) = \frac{hc}{4\pi} N_\nu\left(z=0\right)$, which is in $\frac{\text{erg}}{\text{cm}^2\text{ s Hz sr}}$. When this is converted to nW $m^{-2}Hz^{-1}sr^{-1}$, we finally obtain the flux νJ_ν in nW $m^{-2}sr^{-1}$. At 550 nm we require νJ_ν =20 nW $m^{-2}sr^{-1}$. Also as mentioned earlier, at 850 microns the difference δ between the diffuse infra-red background as measured by FIRAS-COBE, and the point source infra-red background as measured by SCUBA is limited as follows:

$$|\delta| \le 0.6 \text{ nW m}^{-2}\text{sr}^{-1} \qquad (60)$$

Thus we require that any IG dust contribution to the far infra-red spectrum at 850 microns must be less than or equal to this limit. These various conditions, and the upper limit $\Omega_{Dust}(0) < 2 \bullet 10^{-4}$ constrain the possible values of $\Omega_{Dust}(0)$.

8.7 Results

In Table 5 we display one choice of $\Omega_{Dust}(0)$ for each model (it is required to be ≤ .0002), as well as the corresponding calculated values of $T_{Dust}(0)$, the flux F in nW m^{-2} sr^{-1} at 850 microns with CMB flux subtracted (F is required to be ≤ 0.6), the rest frame B-band extinction A_B at z=0.5 (required to be ≤ A_{crit}(z=.5)=.41), and the rest frame color excess E(B-V) at z=0.5 (required to be ≤0.04). In general, F, A_B, and E(B-V) are all proportional to $\Omega_{Dust}(0)$ over a wide range of the latter quantity.

Table 5.

I.G. Model	$\Omega_{Dust}(0)$, in units of 10^{-4}	$T_{Dust}(0)$, Deg K	F @ 850 microns	A_B(z=0.5)	E_{B-V}(z=0.5)
1	1.70	13.9	.048	.13	.040
2	1.0	12.8	.084	.197	.040
3	.56	12.5	.107	.24	.040
4	.24	12.4	.121	.27	.040
5	.65	15.7	.048	.32	.040
6	.65	12.7	.15	.41	.015
7	.60	8.9	.48	.41	.002
8	.29	6.2	.6	.20	.000

Values at or close to the limits imposed by observational (and theoretical) constraints are indicated in red, while calculated z=0.5 rest frame B-band extinctions that are more than 1/2 of 0.41 are indicated in green. We see from Table 5 that it is possible to account for more than 1/2 of the observed dimming without violating the various constraints in Models I.G.3, 4, ,5, 6, and 7; but only model I.G. 6 accounts for all of the dimming without coming very close to violating one or more of the constraints.

We now discuss various features of the results in some detail.

•Fig. 24 shows how the dust temperature evolves as a function of z, for Models I.G. 1-4, when $\Omega_{Dust}(0)$ is as shown in Table 5. The curves for the other models are similar.

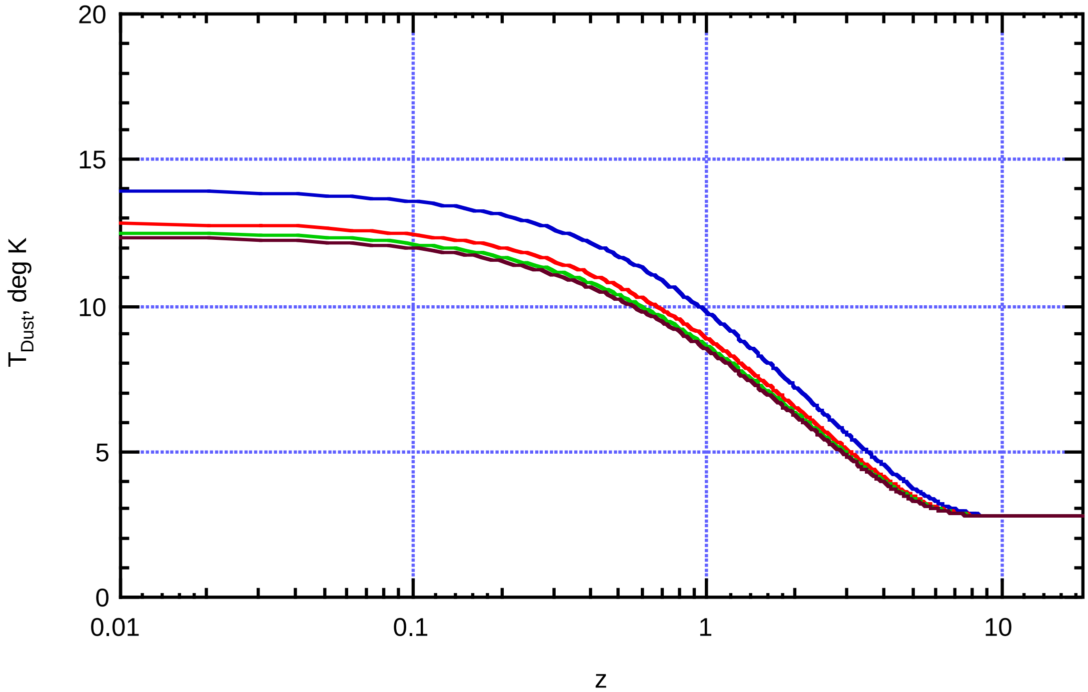

Fig. 24. Evolution of dust temperatures as a function of z. Blue: I.G.1; Red: I.G.2; Green: I.G.3, Purple: I.G.4.

• Fig. 25 displays typical results for the calculated flux as a function of wavelength. (In this example we show the results for Model I.G.4). The blue curve (#1) is the CMB flux. The curves 2,3 describe the calculated flux due to starlight and dust, with the CMB component subtracted, for $\Omega_{Dust}(0)$= 2.35•10^{-5} and 2.35•10^{-7} respectively. It is easy to see that the flux distribution in the UV, visible, and near-infra-red is essentially <u>independent</u> of $\Omega_{Dust}(0)$. However, in the far infra-red the flux is <u>proportional</u> to $\Omega_{Dust}(0)$. Curves for the other models are qualitatively similar.

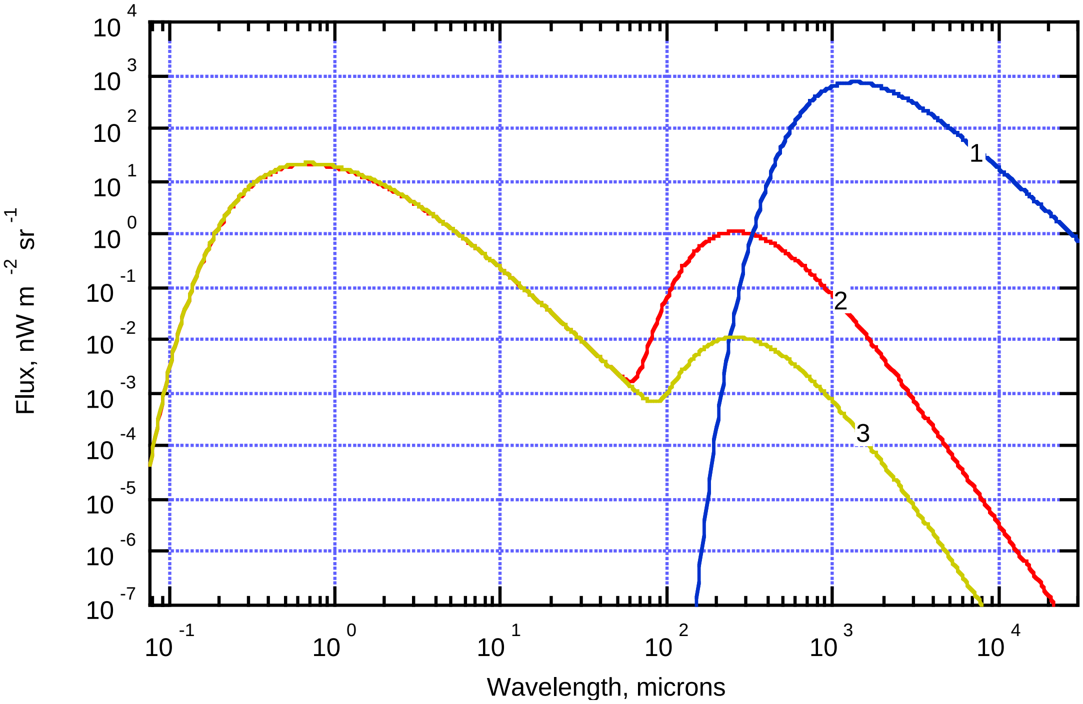

Fig. 25 Calculated flux at z=0 versus wavelength in Model I.G. 4. Curve #1 (Blue): CMB flux. Curves #2,3: $\Omega_{Dust}(0)=2.35 \bullet 10^{-5}$, $2.35 \bullet 10^{-7}$ respectively.

• Figs. 26-30 show the calculated rest frame B-band extinctions A_B and color excesses E due to extinction: B-U, B-V, B-R, and B-I as a function of z for Models I.G. 3, 4, 5, 6, and 7. In each case, $\Omega_{Dust}(0)$ is the same value as shown in Table 5.

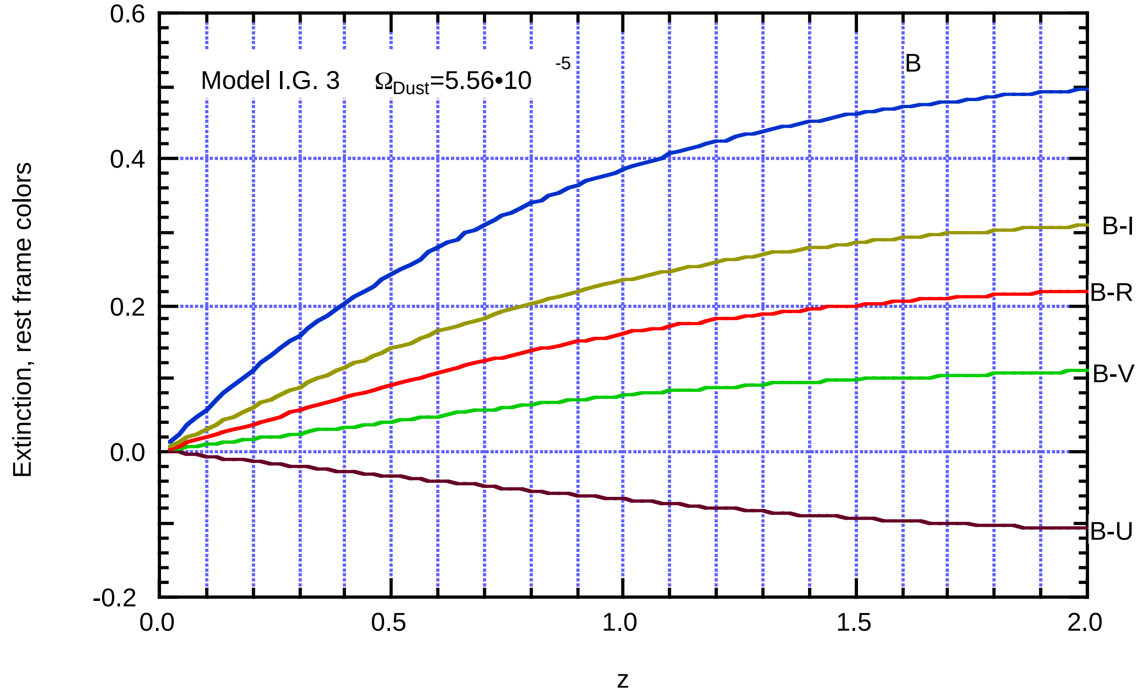

Fig. 26. Model I.G. 3

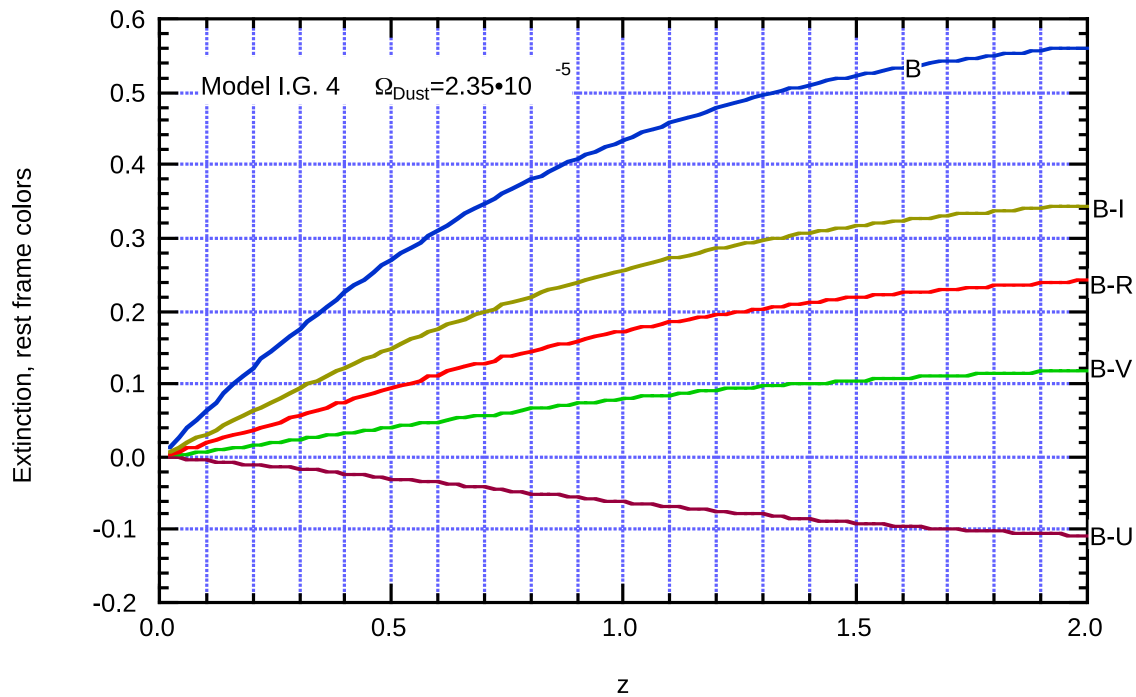

Fig. 27 Model I.G. 4

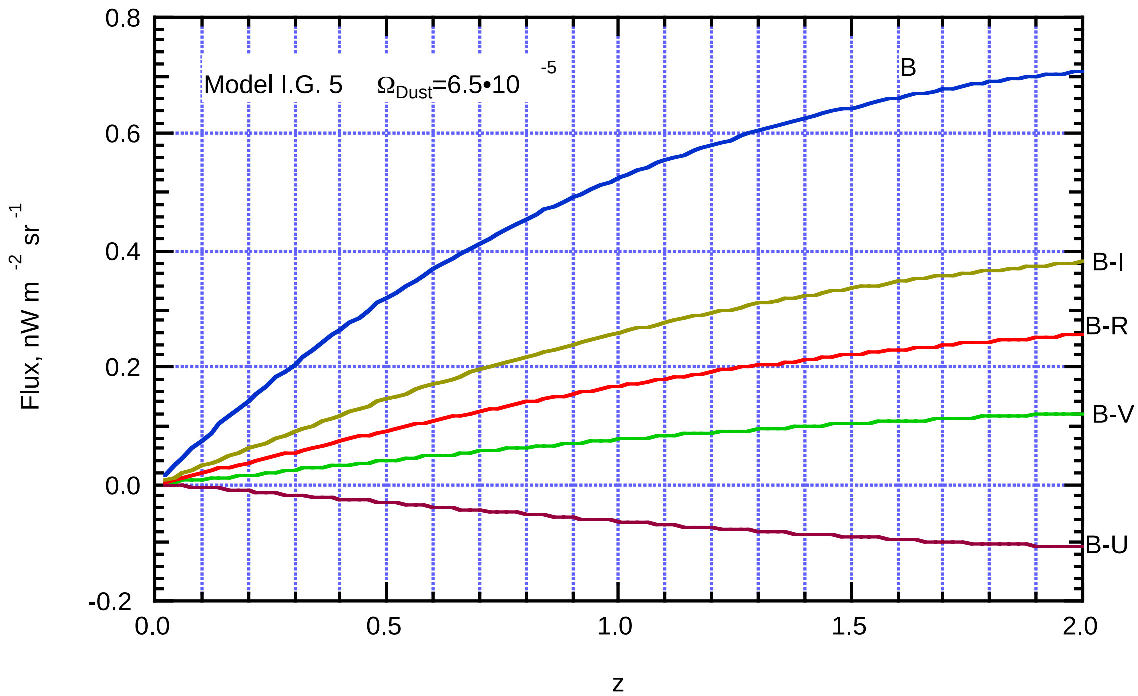

Fig. 28 Model I.G. 5

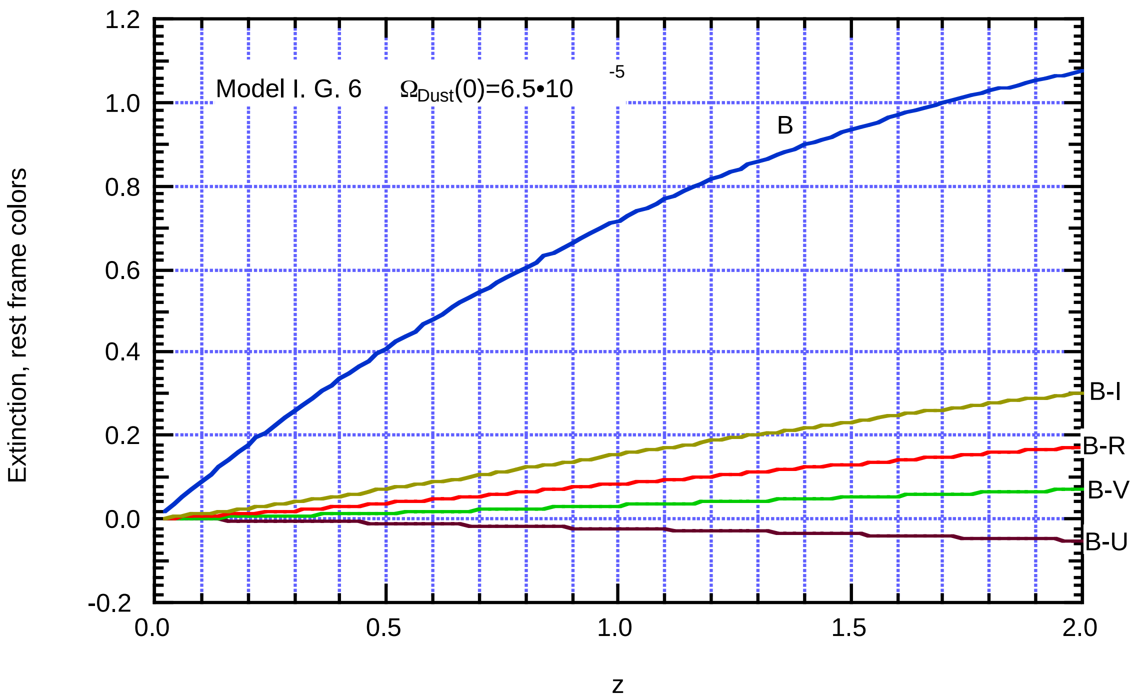

Fig.29 Model I.G.6

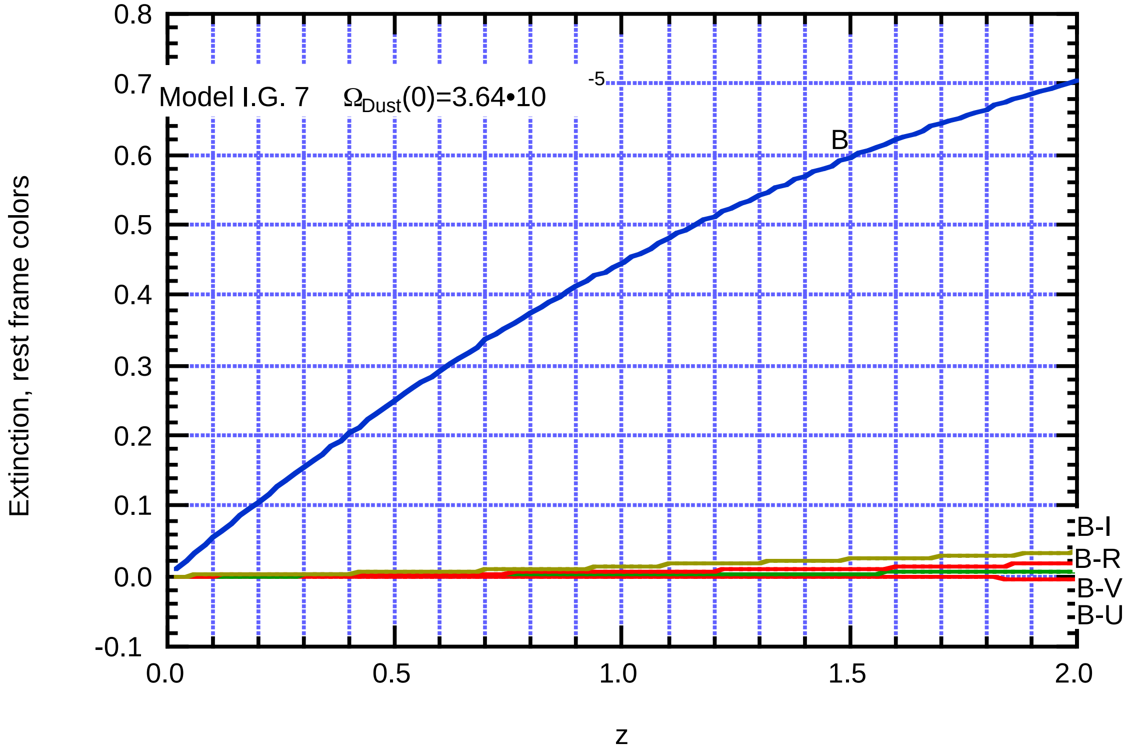

Fig. 30. Model I.G. 7

There are several important trends that can be seen in these figures. First, the derivative of the rest-frame B-band extinction A_B with respect to z generally increase as we go from Model I.G.2 to 7. Thus at z=1.7 we find the following values:

Model I.G 2	A_B= 0.375
3	0.479
4	0.543
5	0.530
6	0.609
7	0.643

Second, the color excesses generally increase as we go from Model I.G. 2 to 4, but then they decrease again in going from Model I.G. 5 to 7:

Model I.G.2	E(B-V)=0.090
3	0.103
4	0.111
5	0.088
6	0.037
7	0.005

It is easy to understand the reasons for these trends qualitatively by recalling the opacity curves for the models (Fig.21). For example, since the opacity of Model I.G.7 is virtually constant over the entire frequency range of interest, we would expect almost no difference in the absorption coefficients at B, V, R, and I. Of course this would also be the case (even more so) for Model I.G. 8, and is true to a lesser extent for Models I.G. 6, and still less for I.G. 5.

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