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thors have proposed models in which such grains thermalize the microwave background (see, e.g., Wickramasinghe et al. 1975; Wright 1982; Hawkins & Wright 1988).

I have calculated the extinction cross section for needles at λ ≤ 10 μm using the ‘discrete dipole approximation’ (see, e.g., Draine 1989) as implemented in the publicly available DDCAT package and using the accompanying graphite dielectric constants ε₁ and ε₂ (see Laor & Draine 1993). Following Wickramasinghe & Wallis (1996), I assume that the graphite ε-axis is perpendicular to the needle so that ε₁ applies for an electric field parallel to the needle axis (see also Bacon 1960). Figure 1 shows curves for various needle diameters d, 0.02 ≤ d[μm] ≤ 0.2, averaged over incident radiation directions, and averaged over an aspect ratio distribution n(L/d) ∝ (L/d)⁻¹ with 4 ≤ L/d ≤ 32. This mass-equipartition distribution was chosen to represent a scattering spectrum from longer needles; laboratory needles grow up to L/d ∼ 1000. The maximal L/d is somewhat arbitrary but largely irrelevant since the short-wavelength behavior depends only weakly on L/d ≥ 8. The results roughly agree with the Mie calculations of Wickramasinghe and Wallis (1996) which use somewhat different optical data.

Major uncertainties in the opacity model include the uncertainties in optical data (see Draine & Lee 1984 for discussion), an unknown impurity content in the needles, and the unknown needle diameter; the model given is intended to be suggestive rather than complete. The key point is that needles generically have an opacity which is higher (κν ∼ 10⁵ cm⁻² g⁻¹) and less wavelength-dependent than that of standard dust.

Several works (Chiao & Wickramasinghe 1972, Ferrara et al. 1990 and 1991, Bartsella et al. 1989) have studied dust ejection from galaxies, all concluding that most spiral galaxies could eject (spherical) graphite dust. These theoretical studies are supported by observations of dust well above the gas scale height in galaxies (Ferrara et al. 1991) and of vertical dust lanes and fingers protruding from many spiral galaxies (Sofue, Wakamatsu & Maln 1994). The high opacity of needles extends over a large wavelength range, hence they are strongly affected by radiation pressure and are even more likely to be ejected than spherical grains. In a magnetized region, charged grains spiral about magnetic field lines. Magnetized gas may escape from the galaxy via the Parker (1970) instability, or grains may escape by diffusing across the lines during the fraction of the time that they are uncharged; see, e.g., Bartsella et al. (1989). Once free of the galaxy², needles would rapidly accelerate and could reach distances of 1 Mpc or more.

Following Hoyle & Wickramasinghe (1988), we estimate the time required for needle ejection and dispersion as follows. A grain with length L, cross section d², specific gravity ρ₀, and opacity κ in an anisotropic radiation field will attain a terminal velocity v given by equating the radiative acceleration κF/ε to the deceleration due to viscous drag of a ≈ (4π²/3)σD²/ρ₀v(σ²/ε²). Here, F is the net radiative flux, and v = (3κ̄Tgas/μM) and p₀ are the gas thermal speed and density. Values applicable for needles in our Galaxy are κ ≃ 10⁵ cm⁻² g⁻¹, ρ₀ ≃ 2 g cm⁻³, v ≃ 10⁻⁴ cm s⁻¹, Tgas ≃ 100K, and F/ε ≃ 10⁻¹³ ergs cm⁻². This gives a terminal velocity

v ≃ 4 × 10⁵[d(0.1μm)]¹/² cm s⁻¹ and a timescale to escape a 100 pc gas layer of ~ 2.5 × 10⁷[d(0.1μm)]¹/² yr. Outside the gas layer, the needle is subject only to radiation pressure. For a rough estimate we assume that the constant acceleration κF/ε ≃ 10⁻⁵ cm s⁻² acts for the time required for the needle to travel a distance equal to the galactic diameter. This takes ~ (2Rc/κF)¹/² ≈ 8 × 10⁷ yr for a galaxy of size R ~ 3 × 10¹⁸ cm and leaves the needle with velocity v ≃ 2.5 × 10⁷ cm s⁻¹. Such a velocity will carry the needle 1 Mpc (twice the mean galaxy separation at z = 1) in ~ 4 Gyr. For comparison, the time between z = 3 (when dust might be forming) and z = 0.5 (when the supernovae are observed) is 5.5 Gyr for Ω = 1 and 7.5 Gyr for Ω = 0.2. These estimates suggest that radiation pressure should be able to distribute the dust fairly uniformly² before z ≃ 0.5.

Dust is known to exist in large quantities (masses ~ 0.1% of the total galaxy mass are often inferred) in bright, high-redshift galaxies (see, e.g., Hughes 1996). These galaxies would preferentially eject dust with higher opacity at long wavelengths (e.g., needles, or fractal/fluffy grains); such grains tend to have a shallower falloff in opacity with wavelength, hence redder than the observed Galactic dust. This selection effect and the estimation of dust escape timescales suggest that if substantial intergalactic dust exists, it should be effectively uniform, and redder than less standard dust.

We can compute the optical depth to a given redshift due to uniform dust of constant comoving density using

\[ \tau(z) = \int_0^z \frac{d\bar{z}}{dz} \frac{(1 + \bar{z})\kappa}{(1 + 4\Omega)^{1/2}}. \]

Figure 1 shows the integrated optical depth to various redshifts for needles with d = 0.1 μm, for Ω = 0.2, h = 0.65 and Ω_{crit} = 10⁻³. Using this information, we can calculate the dust mass necessary to account for the observations if Ω_{Λ} = 0. The difference between an Ω = 0.2, Ω_{Λ} = 0.0 model and a model with Ω = 0.24, Ω_{Λ} = 0.76 (the favored fit of R98) is about 0.2 magnitudes at z = 0.7. In the d = 0.1 μm needle model this requires Ω_{crit} = 1.6 × 10⁻². Matching an Ω = 1, Ω_{Λ} = 0 universe requires about 0.5 magnitudes of extinction at z = 0.7 and Ω_{crit} = 4.5 × 10⁻³.

A reddening correction based on standard dust properties, like that used in R98, would not eliminate this effect. R98 effectively estimates extinction using rest-wavelength
(after K-correction) $B-V$ color and the Galactic reddening law. For standard dust this would be reasonable even for a cosmological dust distribution, since the reddening would still occur along the redshift-corrected $B$ and $V$ frames. But Figure 1 shows that this does not hold for needles: the $d = 0.1\,\mu m$ needle distribution only gives $(B-V) = 0.06\,A_V$ up to $z = 0.7$. The supernova group method would K-correct the $B$ and $V$ magnitudes, then convert this (rest frame) $B-V$ into an extinction based on the Galactic $(B-V) = 0.32\,A_V$. It would therefore not be surprising for the systematic extinction to go undetected.

Studies of redshift-dependent reddening (e.g. Wright 1981, Wright & Malkan 1987, Cheng et al. 1991) in far-UV (rest frame) quasar spectra put limits on a uniform dust component, but these are more sensitive to high redshifts, at which the needles would not yet have formed and uniformly dispersed. In addition, it is clear from Figure 1 that for thick needles the flatness of the opacity curve would lead to a very small shift in the quasar spectral index up to $z = 1$.

Another available constraint, the metallicity of Ly-$\alpha$ clouds, is probably not relevant; because the dust formation and ejection (due to radiation pressure) from galaxies is independent of the enrichment mechanism of the clouds (presumably population III enrichment or gas ‘blowout’ from galaxies), there is no clear connection between the mass of metal gas in the clouds and the mass of needle dust in the IGM.

To estimate the fraction of carbon locked in the needle dust, we would like to know $\Omega_2$ at $0.5 \lesssim z \lesssim 3$. The current value of $\Omega_2$ should be bounded above by the metal fraction of large clusters, which are the best available approximation to a closed system that is a fair sample of the universe. Clusters tend to have $\sim 1/2$ solar metallicity (e.g., Mushotzky et al. 1996), and $\sim 10\%$ of their mass in gas (e.g., Bahcall 1997 for a summary), giving $\Omega_2 \lesssim 10^{-3}$. This compares reasonably well with an upper bound on universal star density estimated from limits on extragalactic starlight (from Peebles 1993) of $\Omega_s < 0.04$; if we extrapolate the Galactic metallicity of $\sim Z_G$, we find $\Omega_2 \sim Z_G \lesssim 4 \times 10^{-4}$. Assuming a current $\Omega_2 \sim 4 \times 10^{-4}$ and that metals are created constantly (conservative, given the higher star formation rate at high $z$) in time from $z = 6$ we find (for both $\Omega = 0.2$ and $\Omega = 1$) that $\Omega_2 (z = 3) \sim 4 \times 10^{-5}$ and $\Omega_2 (z = 0.5) \sim 2 \times 10^{-4}$, which agrees with recent estimates by Renzini (1998). Even such crude approximations are very vulnerable, but suggest that the needed amount of needle dust is reasonable.

The needle model is falsifiable in several ways. First, the needle opacity spectrum is not perfectly flat, especially for small $d$. Observations over a long wavelength span might reveal a redshift-dependent systematic change in certain colors.

Next, the needles take some minimum time to form, then more time to achieve a uniform cosmic distribution. Thus at high enough redshift the dispersion in supernova brightness discussed in R98 appears. Moreover, at $z = 1.5$ the difference between the $\Omega = 0.2$, $\Omega_\Lambda = 0$ model with dust and the $\Omega = 0.24$, $\Omega_\Lambda = 0.76$ model sans dust is $\lesssim 0.2$ mag, which should eventually be observable.

I shall not attempt to address the question of galaxy counts here. As commented in R98, grey dust would exacerbate the ‘problem’ of unexpectedly high galaxy counts at high-z, but the magnitude of such an effect would depend upon the dust density field’s redshift evolution, and a full discussion of the galaxy count data as a constraint on the model (requiring also an understanding of galaxy evolution) is beyond the scope of this letter.

Galactic observations probably cannot disprove the model, since needles with the properties most different than those of Galactic dust would be ejected with high efficiency. Moreover, dust with needle-like characteristics may have been detected by COBE (Wright et al. 1991; Reach et al. 1995; Dwek et al. 1997) as a minor ‘very cold’ component of Galactic dust. Such a component is best explained by dust with a hitherto-unknown IR emission feature, or by fluffy/fractal or needle dust (Wright 1993) and could represent a residual needle component with about 0.02-0.4% of the standard dust mass.\(^5\)

On the other hand, the dust cannot escape from clusters, which have much higher mass/light ratios, so needles formed after the formation of a cluster should remain trapped within. Studies of background quasar counts (Boggia & Wagner 1973; Boyle et al. 1988; Romani & Mazo 1992), cooling flows (Hu 1992), and IR emission (Stickel et al. 1998) of rich clusters indicate extinctions $A_V \sim 0.2 - 0.4$ mag and standard dust masses of $M_d^{\text{obs}} \sim 10^{18} M_\odot$. Denoting by $Z_d$, $M_d$, and $M_d^{\text{obs}}$ the mean cluster metallicity, total mass and gas mass, we can estimate the fraction of metals in dust $\chi_d$ to be

$$\chi_d = \frac{M_d}{M_d^{\text{obs}}} \frac{M_d^{\text{obs}}}{Z_d} \sim 10 \times 10^{-5}/0.01 = 0.01,$$

using $M_d \sim 10^{15} M_\odot$. Comparing this to the $\chi_d \sim 1$ typical of our Galaxy would indicate dust destruction efficiency of $\lesssim 99\%$ in clusters. An earlier calculation gave $\Omega_{\text{dust}}/\Omega_s \gtrsim 0.1$ for the intergalactic needles. Assuming the calculated dust destruction, this predicts $M_d^{\text{obs}}/M_d \sim 0.1$. The needles are about five times as opaque in optical as standard dust, so this gives an optical opacity ratio of $\sim 0.5$. If these estimates are accurate, comparison of nearby cluster supernovae to nearby non-cluster supernovae at fixed distance should reveal a mean systematic difference of $A_V \gtrsim 0.03 - 0.06$ in fluxes after correction for reddening.\(^6\) The Mt. Stromlo Abell cluster supernova search (Reiss et al. 1998), currently underway, should make such an analysis possible. Note that uncertainties in the needle opacity relative to standard dust will not affect the cluster prediction which (modulo the quantitative uncertainties) should hold unless clusters destroy needles more efficiently than standard dust.

3. CONCLUSIONS

I have argued that the reduction of supernova fluxes at high redshift could be caused by a uniform distribution of intergalactic dust.

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\(^5\) Of course, if the needles were also assumed to form in the population III objects their density should then relate to the Ly-\(\alpha\) metallicity.

\(^6\) The needles absorb about 5x as effectively (per unit mass) in the optical where most Galactic radiation resides, and the ‘very cold’ component emits between 1% and 2% of the total FIR dust luminosity (Reach et al. 1996).
Both theoretical arguments and observational evidence strongly suggest that some dust should be ejected from galaxies. Dust with high opacity (especially at long wavelengths, where most of the luminosity of high-redshift starburst galaxies resides) would be preferentially ejected. But this is exactly the sort of dust which would both redden less than standard dust, and require less dust mass to produce the observed effect. This letter develops a specific model of intergalactic dust composed of carbon needles—a theoretically reasonable, even expected, form of carbon dust—with conservative properties. The supernova data can be explained by a quantity of carbon needles which is plausible in light of rough estimates of the universal metal abundance.

Because the dust distribution is effectively uniform, it does not induce a dispersion in the supernova magnitudes, and because it absorbs more efficiently than standard dust, it does not require an unreasonable mass. Finally, because the dust is created and ejected by high-z galaxies, it does not overly obscure very high redshift galaxies or quasars. Thus the key arguments given in R98 against ‘grey’ dust do not apply. The dust of the proposed model should, however, produce independent signatures of its existence; one is a systematic difference in fluxes between cluster and non-cluster supernovae which may be detectable in on-going surveys. Finally, the needle model is only one specific model for intergalactic dust. Other possible ‘dust’ types are fractal dust (e.g. Wright 1987), platelets (e.g. Donn & Sears 1963; Bradley et al. 1983), hollow spheres (Layzer & Hively 1973), or hydrogen snowflakes.

The explanation of reduced supernova flux at high redshift described in this letter depends upon the plausible but still speculative assumption that the intergalactic dust distribution has significant mass, and is dominated by grains with properties exemplified by those of carbon needles. The probability that this is the case should be weighed against the severity of the demand that the explanation favored by Riess et al. and Perlmutter et al. places on a solution of the vacuum energy (or cosmological constant) problem: the expected value of the vacuum energy density at the end of the GUT era must be reduced by some as yet unknown process, not to zero, but to a value exactly one hundred orders of magnitude smaller.

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REFERENCES


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IN PROOF

Two recent papers bear upon this Letter. Kochanek et al. (1998, astro-ph/9811111) find that dust in early-type high-z galaxies reddens more than ‘standard’ dust. Needles may escape ellipticals, but the lensing technique applied to clusters would be an excellent test of the needle model.

Perlmutter et al. (1998, Ap. J., accepted) find no statistically significant different in mean reddening between low-z and high-z samples; however, the $B-V \approx 0.01$ mag that my fiducial model predicts fits easily within their 1-$\sigma$ errors.
Fig. 1.—Top: Carbon needle opacity curves for aspect ratio distribution $n \sim (L/d)^{-1}$ and diameters $d = 0.02, 0.04, 0.1, 0.2 \mu$m (dotted, dashed, solid and triple-dot-dashed, respectively). Also included are central U, B, V and I frame wavelengths and a ‘Draine & Lee’ dust curve (long-dashed) calculated using the Laor & Draine (1993) method. Bottom: Integrated extinction to various redshifts for $d = 0.1 \mu$m needles for $\Omega = 0.2$ and $\Omega_{\text{needle}} = 10^{-5}$. $z=0.01$