DUST VERSUS COSMIC ACCELERATION

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ABSTRACT

Two groups have recently discovered a statistically significant deviation in the fluxes of high-redshift Type Ia supernovae from the predictions of a Friedmann model with a zero cosmological constant. In this Letter, I argue that bright, dusty, starburst galaxies would preferentially eject a dust component with a shallower opacity curve (hence less reddening) and a higher opacity/mass than the observed galactic dust that is left behind. Such dust could cause the falloff in flux at high redshift without violating constraints on reddening or metallicity. The specific model presented is of needle-like dust, which is expected from the theory of crystal growth and has been detected in samples of interstellar dust. Carbon needles with conservative properties can supply the necessary opacity and would very likely be ejected from galaxies as required. The model is not subject to the arguments given in the literature against gray dust but may be constrained by future data from supernova searches done at higher redshift, in clusters, or over a larger frequency range.

Subject headings: cosmology: observations — dust, extinction — radiative transfer

1. INTRODUCTION

Recently, two separate groups have interpreted their observations of Type Ia supernovae as evidence for acceleration in the cosmic expansion, presumably caused by a nonzero cosmological constant (Riess et al. 1998, hereafter R98, and Perlmutter et al. 1998). Using the supernovae as standard candles (after correction for the relation between luminosity and light-curve shape), both groups find a progressive dimming of supernovae at high redshift relative to the predictions of a flat, matter-dominated model or even an open model with a zero cosmological constant. There are at least two explanations for this dimming that are unrelated to the cosmological parameters: evolutionary effects and dust. The two observational groups have expended considerable effort in attempting to account for such systematics, but in this Letter, I argue that the obscuration of distant supernovae by a cosmological distribution of dust is *not* ruled out, by developing a simple intergalactic dust model that is reasonable in its creation and dispersion, has reasonable physical properties, and could cause the observed effect without violating constraints such as those noted in R98.

The standard way to estimate dust extinction, used by the supernova groups, is to apply a relation between reddening and extinction derived from Galactic data (see, e.g., Cardelli, Clayton, & Mathis 1989). This relation is a result of the frequency dependence of the opacity curve of the absorbing dust, which can be measured well for Galactic dust at wavelengths $\lambda \lesssim 100$ μm and fitted by theoretical models of graphite and silicate dust in the form of small spheres with a distribution of radii (Draine & Lee 1984; Draine & Shapiro 1989). Because the opacity of this "standard" dust falls off rather quickly with increasing wavelength for $\lambda \gtrsim 0.1$ μm, attenuated light is significantly reddened.

The weakness of this method when applied to a new situation is the necessary assumption that the same extinction-reddening relation holds, even though the dust may be of a different species; standard techniques would not correct for dust that causes extinction without significant reddening. For the same reason, an effectively uniform intergalactic distribution of non-reddening dust could remain undetected by reddening studies such as those of Wright & Malkan (1988) and Cheng, Gaskell, & Koratkar (1991).

2. A SPECIFIC MODEL WITH CARBON NEEDLES

To make this idea concrete, let us begin with the theory of dust formation. Very small dust grains are believed to form in a vapor-solid transition, via a process of crystal formation; these grains may then coagulate into larger ones. In small grain formation, nuclei form first, and then they grow as surface nucleation occurs on their faces. Surface nucleation creates steps that grow along the face, adding a new layer and increasing the crystal size. But environments of low supersaturation (as may commonly occur astrophysically) strongly inhibit surface nucleation. In such cases, grains may still grow by the mechanism of a "screw dislocation" (see, e.g., Frank 1949 and Sears 1955) or by growth of a rolled-up platelet (Bacon 1960), forming one-dimensional "needles" like those commonly found in laboratory experiments (see, e.g., Nabarro & Jackson 1958).

Moreover, needles can grow rapidly where "spherical" dust cannot; thus, in some situations, needles can outcompete spherical dust for available metals. This reasoning led Donn & Sears (1963) to predict that interstellar dust could be dominated by needle-type dust. These predictions were partially borne out by the discovery of estatite needles in captured interstellar dust (Bradley, Brownlee, & Veblen 1983). The needles were not the dominant component, but their discovery does demonstrate that vapor-solid transitions occur astrophysically and that astrophysical needles can form by the same mechanism as in laboratories (they contained screw dislocations). Conducting needles are physically interesting because they act as antennas, absorbing electromagnetic radiation more effectively than standard dust. Several authors 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 $\lambda \leq 10$ μm using the "discrete dipole approximation" (see, e.g., Draine 1988) as implemented in the publicly available DDSCAT package and using the accompanying graphite dielectric constants $\epsilon_\perp$ and $\epsilon_\parallel$ (see Laor & Draine 1993). Following Wickramasinghe & Wallis (1996), I assume that the graphite c-axis is perpendicular to the needle, so that $\epsilon_\perp$ applies for an electric field parallel to the needle axis (see also Bacon 1960). Figure 1 shows curves for various needle diameters d, $0.02 \leq d(\mu$m$) \leq 0.2$, averaged over incident radiation directions

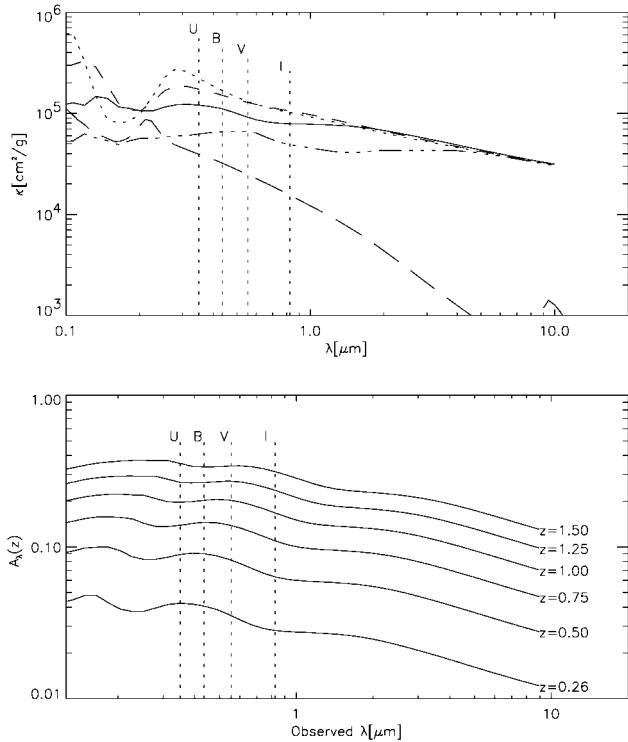FIG. 1.—*Top*: carbon needle opacity curves for aspect ratio distribution $n \propto (L/d)^{-1}$ and diameters $d = 0.02$, 0.04, 0.1, and 0.2 μm (*dotted, dashed, solid, and triple-dot–dashed curves, respectively*). The central *U*, *B*, *V*, and *I* frame wavelengths and a "Draine & Lee" dust curve (*long-dashed curve*) calculated using the Laor & Draine (1993) method are also included. *Bottom*: integrated extinction to various redshifts for $d = 0.1$ μm needles for $\Omega = 0.2$ and $\Omega_{needle} = 10^{-5}$.

and averaged over an aspect ratio distribution $n(L/d) \propto (L/d)^{-1}$ with $4 \le L/d \le 32$. This mass-equipartition distribution was chosen to represent a shattering spectrum from longer needles; laboratory needles grow up to $L/d \sim 1000$. The maximal L/d is somewhat arbitrary but largely irrelevant since the short-wavelength behavior depends only weakly on $L/d \gtrsim 8$. The results roughly agree with the Mie calculations of Wickramasinghe & 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[1]; the model given is intended to be suggestive rather than complete. The key point is that needles generically have an opacity that is higher ($\kappa_V \simeq 10^5$ cm^2 g^{-1}) and less wavelength-dependent than that of standard dust.

Several works (Chiao & Wickramasinghe 1972; Ferrara et al. 1990, 1991; Barsella et al. 1989) have studied dust ejection from galaxies, and they all conclude 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, & Malin 1994). The high opacity of needles ex-

tends over a large wavelength range; hence, they are strongly affected by radiation pressure and are even more likely 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 (1979) instability, or grains may escape by diffusing across the lines during the fraction of the time that they are uncharged (see, e.g., Barsella et al. 1989). Once free of the galaxy,[2] needles would accelerate rapidly 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 d^2, specific gravity ρ_m, and opacity κ in an anisotropic radiation field will attain a terminal velocity v given by equating the radiative acceleration $\kappa F/c$ to the deceleration due to the viscous drag of $a \approx (4v^2/\pi d)(\rho_{gas}/\rho_m) + O(u^2/v^2)$. Here F is the net radiative flux, and $u = (3kT_{gas}/m_H)$ and ρ_{gas} are the gas thermal speed and density, respectively. Values applicable for needles in our Galaxy are $\kappa \simeq 10^5$ cm^2 g^{-1}, $\rho_m \simeq 2$ g cm^{-3}, $\rho_g \simeq 10^{-24}$ g cm^{-3}, $T_{gas} \sim 100$ K, and $F/c \sim 10^{-13}$ ergs cm^{-3}. These give a terminal velocity of $v \simeq 4 \times 10^5 (d/0.1$ μm$)^{1/2}$ cm s^{-1} and a timescale to escape a 100 pc gas layer of $\sim 2.5 \times 10^7 (d/0.1$ μm$)^{-1/2}$ yr. Outside the gas layer, the needle is subject only to radiation pressure. For a rough estimate, we assume that the constant acceleration $\kappa F/c \sim 10^{-8}$ cm s^{-2} acts for the time required for the needle to travel a distance equal to the galactic diameter. This takes $\sim (2R/\kappa F)^{1/2} \simeq 8 \times 10^7$ yr for a galaxy of size $R \sim 3 \times 10^{22}$ cm and leaves the needle with velocity $v \sim 2.5 \times 10^7$ 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 $\Omega = 1$ and 7.3 Gyr for $\Omega = 0.2$. These estimates suggest that radiation pressure should be able to distribute the dust fairly uniformly[3] before $z \simeq 0.5$.

Dust is known to exist in large quantities (masses $\sim 0.1\%$ 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, they redden less 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 should redden less than standard dust.

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

$$\tau_\lambda(z) = \left(\frac{c}{H_0}\right) \rho_0 \Omega_{needle} \int_0^z dz' \frac{(1 + z')\kappa[\lambda/(1 + z')]}{(1 + \Omega z')^{1/2}}. \quad (1)$$

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[1] The needle diameter is particularly important, but it is difficult to justify any a priori estimate of its value. For the sake of the argument at hand, I take $d = 0.1$. Note that a distribution of diameters would likely simply be dominated by the low-diameter cutoff.

[2] A grain leaving the disk would be sputtered by gas in the hot galactic halo, but the resulting mass loss is less than 20% for the 0.01 μm silicate spheres and even less for faster moving or larger grains (Ferrara et al. 1991), so the effect on the needles would be very small.

[3] Using the model of Hatano, Branch, & Deaton (1997), R98 argues that dust confined to galaxies would cause too large a dispersion in supernova fluxes. For the dust to create less dispersion than observed, they must merely be "uniform" enough that a typical line of sight (of length $\sim cH_0^{-1}$) passes through many clumps of size $\sim D$ and separation $\sim \lambda$, i.e., $1/(cH_0^{-1}D^2/\lambda^3)^{1/2} \lesssim 1$ (the observed dispersion in R98 is 0.21 mag, similar to the necessary extinction). This is easily satisfied for needles traveling $\gtrsim 50$ kpc from their host galaxies.

Figure 1 shows the integrated optical depth to various redshifts for needles with $d = 0.1$ μm, for $\Omega = 0.2$, $h = 0.65$, and $\Omega_{\text{needle}} = 10^{-5}$. Using this information, we can calculate the dust mass necessary to account for the observations if $\Omega_\Lambda = 0$. The difference between an $\Omega = 0.2$, $\Omega_\Lambda = 0.0$ model and a model with $\Omega = 0.24$, $\Omega_\Lambda = 0.76$ (the favored fit of R98) is about 0.2 mag at $z = 0.7$. In the $d = 0.1$ μm needle model, this requires $\Omega_{\text{needle}} = 1.6 \times 10^{-5}$. Matching an $\Omega = 1$, $\Omega_\Lambda = 0$ universe requires about 0.5 mag of extinction at $z = 0.7$ and $\Omega_{\text{needle}} = 4.5 \times 10^{-5}$.

A reddening correction based on standard dust properties, like that used in R98, would not eliminate this effect. R98 effectively estimate 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 across the redshift-corrected B and V frames. But Figure 1 shows that this does not hold for needles: the $d = 0.1$ μm needle distribution only gives $(B - V) = 0.06A_V$ up to $z = 0.7$. The supernova group method would K-correct the B and V magnitudes, and then it would convert this (rest-frame) $B - V$ into an extinction based on the Galactic $(B - V) = 0.32A_V$. It would therefore not be surprising for the systematic extinction to go undetected.

Studies of redshift-dependent reddening (see, e.g., Wright 1981; Wright & Malkan 1988; Cheng et al. 1991) in far-UV (rest-frame) quasar spectra put limits on a uniform dust component, but these are most 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 Lyα 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 intergalactic medium.[4]

To estimate the fraction of carbon locked in the needle dust, we would like to know Ω_Z at $0.5 \lesssim z \lesssim 3$. The current value of Ω_Z 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 $\sim\frac{1}{2}$ solar metallicity (see, e.g., Mushotsky et al. 1996) and $\sim$10% of their mass in gas (see, e.g., Bludman 1998 for a summary), giving $\Omega_Z \lesssim 10^{-3}$. This compares reasonably well with an upper bound on the universal star density estimated from limits on extragalactic starlight (from Peebles 1993) of $\Omega_* < 0.04$: if we extrapolate the galactic metallicity of $\sim Z_\odot$, we find $\Omega_Z \sim Z_\odot \Omega_* \lesssim 4 \times 10^{-4}$. Assuming a current $\Omega_Z \sim 4 \times 10^{-4}$ and that metals are created constantly (which is 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 $\Omega_Z(z = 3) \sim 4 \times 10^{-5}$ and $\Omega_Z(z = 0.5) \sim 2 \times 10^{-4}$, which agrees with recent estimates by Renzini (1998). Even such crude approximations are very vulnerable but suggest that the needed amount of needle mass 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 and then more time to achieve a uniform cosmic distribution. Thus, at high enough redshift, the dispersion in supernova brightnesses 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 without dust is $\simeq$0.2 mag, which should eventually be observable.

I shall not attempt to address the question of galaxy counts here. As commented in R98, gray dust would exacerbate the "problem" of unexpectedly high galaxy counts at high z, but the magnitude of such an effect would depend on 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 that formed *after* the formation of a cluster should remain trapped within. Studies of background quasar counts (Bogart & Wagoner 1973; Boyle, Fong, & Shanks 1988; Romani & Maoz 1992), cooling flows (Hu 1992), and IR emission (Stickel et al. 1998) of rich clusters indicate extinctions of $A_V \sim 0.2$–0.4 mag and standard dust masses of $M_{\text{cl}}^{\text{dust}} \sim 10^{10}$ $M_\odot$. Denoting Z_{cl}, M_{cl}, and $M_{\text{cl}}^{\text{gas}}$ as the mean cluster metallicity, total mass, and gas mass, respectively, we can estimate the fraction of metals in dust χ_{cl} to be

$$\chi_{\text{cl}} = \frac{M_{\text{cl}}}{M_{\text{cl}}^{\text{gas}}} \frac{M_{\text{cl}}^{\text{dust}}}{M_{\text{cl}}} Z_{\text{cl}}^{-1} \simeq 10 \times 10^{-5}/0.01 = 0.01, \quad (2)$$

using $M_{\text{cl}} \sim 10^{15}$ $M_\odot$. Comparing this with the $\chi_{\text{gal}} \lesssim 1$ typical of our Galaxy would indicate a dust destruction efficiency of $\lesssim$99% in clusters. An earlier calculation gave $\Omega_{\text{needle}}/\Omega_Z \gtrsim 0.1$ for the intergalactic needles. Assuming the calculated dust destruction, this predicts $M_{\text{cl}}^{\text{needle}}/M_{\text{cl}}^{\text{dust}} \sim 0.1$. The needles are about 5 times as opaque in optical as standard dust, so this gives an optical opacity ratio of $\sim$0.5. If these estimates are accurate, a comparison of nearby cluster supernovae with nearby noncluster supernovae at a fixed distance should reveal a mean systematic difference of $A_V \gtrsim 0.03$–0.06 in fluxes *after* correction for reddening.[6] The Mount 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

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[4] Of course, if the needles were also assumed to form in the Population III objects, their density should then relate to the Lyα metallicity.

[5] The needles absorb about 5 times as effectively (per unit mass) in the optical where most galactic radiation resides, and the very cold component emits between 0.1% and 2% of the total far-IR dust luminosity (Reach et al. 1995).

[6] Similar arguments *might* apply to elliptical galaxies, from which dust ejection is less efficient than from spiral galaxies.

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. Both theoretical arguments and observational evidence suggest strongly 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 ejected preferentially. But this is exactly the sort of dust that would both redden less than standard dust and require less dust mass to produce the observed effect. In this Letter, I develop a specific model of intergalactic dust that is 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 that 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 "gray" dust do not apply. However, the dust of the proposed model should provide independent signatures of its existence; one is a systematic difference in fluxes between cluster and noncluster supernovae that may be detectable in ongoing surveys. Finally, the needle model is only one specific model for intergalactic dust. Other possible "dust" types are fractal dust (see, e.g., Wright 1987), platelets (see, e.g., Donn & Sears 1963 and 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 on 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 R98 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 grand unified theory era must be reduced by some as yet unknown process, not to zero but to a value exactly 100 orders of magnitude smaller.

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Note added in proof.—Two recent papers bear upon this Letter. C. S. Kochanek et al. (astro-ph/9811111 [1998]) 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.

S. Perlmutter et al. (ApJ, in press [1998]) find no statistically significant difference in mean reddening beween low-z and high-z samples; however, the $B - V \simeq 0.01$ mag that my fiducial model predicts fits easily within their 1 σ errors.