SIMULATING THE EFFECTS OF INTERGALACTIC GRAY DUST
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ABSTRACT
Using a high-resolution cosmological hydrodynamic simulation, we present a method to constrain extinction due to intergalactic gray dust based on the observed magnitudes of distant Type Ia supernovae. We apply several simple prescriptions to relate the intergalactic dust density to the gas density in the simulation, thereby obtaining dust extinctions that may be directly compared with the observed distribution of supernova magnitudes. Our analysis is sensitive to the spatial distribution of gray dust but is not dependent on its intrinsic properties, such as its opacity or grain size. We present an application of our technique to the supernova data of Perlmutter et al., who find that their high-redshift sample is ~0.2 mag fainter than the expectation for a nonaccelerating, low-density universe. We find that for gray dust to be responsible, it must be distributed quite smoothly (e.g., tracing intergalactic gas). More realistic dust distributions, such as dust tracing the metal density, are inconsistent with observations at the 1.5–2 σ level. Upcoming observations and improved modeling of the dust distribution should lead to stronger constraints on intergalactic gray dust extinction.

Subject headings: cosmology: observations — dust, extinction — large-scale structure of universe

1. INTRODUCTION
Recent observations of Type Ia Supernovae (SNe) at redshifts of up to z ~ 0.8 (Riess et al. 1998; Perlmutter et al. 1999, hereafter P99) have made possible classical cosmological tests that require standard candles, such as the magnitude-redshift relation. The most dramatic result is that these SNe appear dimmer (by ~0.2 mag) at high redshift than would be predicted in a nonaccelerating universe, suggesting at face value that we live in an accelerating universe. However, other explanations are possible, including the one we consider here, namely that distant SNe are dimmer due to extinction by intergalactic dust.

As distant standard candles, SNe are sensitive probes of extinction in the intergalactic medium (IGM). The distribution of matter in the IGM may now be modeled accurately in the context of modern cosmology using hydrodynamic simulations (see, e.g., Cen et al. 1994; Hernquist et al. 1996; Davé et al. 1999). The resulting IGM is not smooth, but rather it traces large-scale structure. If such structure contains not only dark matter and gas but also dust, there will be significant variations in SNe brightnesses due to intervening extinction. Observationally, the distribution of Type Ia SNe magnitudes has a very small dispersion (P99). Thus, by comparing simulations to the distribution of observed brightnesses, we can set limits on the amount of dust extinction and possibly constrain its spatial distribution with respect to intergalactic gas. In this Letter, we present a technique for doing this and apply it to the SNe observations of P99.

Intergalactic gray dust has been examined in a series of papers by Aguirre (1999a, 1999b) and Aguirre & Haiman (2000), who develop a scenario in which small grains are preferentially destroyed during ejection from galaxies, polluting the IGM with large dust grains that are effectively gray in the bandpasses of the SN data. This grayness is necessary in order to violate tight limits on reddening on SN data, which imply that galactic-type dust would provide negligible absorption (P99). Furthermore, a significant fraction of the dust must reside in the IGM. If the gray dust causing extinction were present only in the interstellar medium of the supernova host galaxy, this would introduce too large a dispersion in observed SN magnitudes (Riess et al. 1998). In this study, we assume that gray dust blends smoothly from galaxies into the surrounding IGM. Our analysis is insensitive to the intrinsic properties of the dust, such as its opacity and grain size, since we use the simulations to translate directly the observed SN magnitude distribution into a dust extinction in magnitudes. It is, however, sensitive to the way in which dust traces the distribution of gas in the IGM, and we will consider several simple but plausible variations of this relation.

2. SIMULATIONS OF INTERGALACTIC DUST
We employ a hydrodynamic simulation (R. Davé et al. 2000, in preparation) of a Λ-dominated cold dark matter model with Ωm = 0.3, ΩΛ = 0.7, H0 = 65 km s Mpc, and θ = 0.8. Our simulation volume is 50 h−1 Mpc with 10 h−1 kpc spatial resolution, having 1443 dark matter and 1443 gas particles, and was evolved from z = 49 to 0 using a gravity treecode combined with a smoothed particle hydrodynamics (SPH) code that was designed for parallel supercomputers having distributed memory (PTreeSPH; Davé, Dubinski, & Hernquist 1997).

In order to obtain dust column densities along lines of sight, we consider three different ways that dust may trace intergalactic hydrogen gas:

1. ρgas ≈ ρgas.—Dust traces gas linearly.
2. ρdust ≈ ρgas.—Dust traces metals linearly.
3. ρdust ≈ ρgas2.—Dust traces gas quadratically.

Since our simulation makes no direct prediction for the metallicity of gas, we adopt a heuristic prescription (cf. Cen & Ostriker 1999) in the second case above. We assume that the metallicity is 10−2 solar if the gas overdensity is less than 10, solar if the overdensity is greater than 1000, and log-linear in between.

To extract dust extinction values from the simulations, we assume that the gas associated with each particle is spread over...
its SPH smoothing volume (see, e.g., Hernquist & Katz 1989). We perform a numerical integration of the gas column density along 5000 rays that are cast through these volumes, and, at the same time, we apply one of the three transformations given above in order to find the relationship between the gas and dust densities. To reach the required path lengths out to \( z \approx 0.5 \), we follow the rays through 26 simulation volumes, each ray entering through a random point on a random face. This yields the column density of dust to \( z = 0.5 \) along each line of sight.

In Figure 1, we show extinction maps of \( 2^2 \times 2^2 \) patches of sky; for Figure 1a \( \rho_{dust} \propto \rho_{gas} \), and for Figure 1b \( \rho_{dust} \propto \rho_{gas}^2 \). The median extinction to \( z = 0.5 \) was set to be equal (to 0.4 mag) for Figures 1a and 1b. In Figure 2, we show how the mean dust extinction and its dispersion vary with redshift. Here the dispersions in all three panels were set to be the same.

3. COMPARISON WITH OBSERVATIONS
We make use of two characteristics of the observed SN data in our comparison, the change with redshift of the dispersion in SN magnitudes and the shape of the histogram of SN magnitudes. As mentioned above, P99 found little difference in the dispersions of two samples with \( \bar{z} \approx 0.05 \) and \( \bar{z} \approx 0.5 \). As they stated, this leaves little room for dispersion due to dust since this dispersion is expected to increase for longer path lengths (see Fig. 2). In order to quantify this and the effect of the distribution shape, we generate simulated SN magnitudes and compare them to the P99 data using a maximum likelihood approach.

The observational data sets that we use are taken from P99 (their Tables 1 and 2), being the high-\( z \) SNe of the Supernova Cosmology Project and the low-\( z \) sample of the Calán-Tololo SN survey (Hamuy et al. 1996). We use 40 (nonreddened SNe) of the former SNe, between \( z = 0.172 \) and \( z = 0.83 \) (\( \bar{z} \approx 0.5 \)), and 16 of the latter SNe, which lie between \( z = 0.02 \) and \( z = 0.101 \) (\( \bar{z} \approx 0.05 \)).

We generate simulated data sets for each dust model described in § 2. For each dust model, we vary two parameters: (1) \( M_\odot \), a cosmological magnitude shift applied to all simulated SNe at a given \( z \) and normalized so that \( M_\odot = 0 \) at \( z = 0.5 \) corresponds to the best-fitting cosmology found by P99 (with \( \Omega_m = 0.28 \) and \( \Omega_\Lambda = 0.72 \)) and (2) \( A_V \), the median V-band magnitude of dust extinction out to \( z = 0.5 \).\footnote{\label{fn:median} We use the median in order to be less sensitive to long tails of the distribution (cf. Fig. 3) when renormalizing extinction values.} \( M_\odot \approx -2 \) then corresponds to an open model with \( \Omega_m \approx 0.3 \), and \( M_\odot \approx -0.4 \) corresponds to an \( \Omega_m = 1 \) model. We generate the simulated data sets as follows:

1. We renormalize the 5000 simulated lines of sight so that the median dust extinction to \( z = 0.5 \) equals \( A_v \).
2. We add the cosmological shift \( M_\odot \).
3. We broaden the magnitude distribution, which involves convoluting it separately with a Gaussian of width given by the observational error of each SN and then adding these distributions together. When doing this, we include an “intrinsic” SN dispersion of \( \sigma_{int} = 0.17 \) mag (P99). Varying this (by \( \pm 0.1 \) mag) makes little difference to the results (see § 4).
4. We then have a distribution of magnitude differences \( \Delta M \) of the SN from the zero point. This zero point corresponds

\[ \Delta M = M_{\text{obs}} - M_{\text{theo}} \]

\[ \text{where } M_{\text{obs}} \text{ is the observed magnitude and } M_{\text{theo}} \text{ is the theoretical magnitude.} \]
to the magnitude of a “standard candle” SN in our fiducial cosmology ($\Omega_m = 0.28$, $\Omega_\Lambda = 0.72$), with $A_V = 0$ (no dust). We truncate this distribution at $\Delta_M^i = 1$ to roughly account for the fact that SNe along lines of sight passing through high-extinction regions would not make it into these magnitude-limited samples.

We derive the probability distribution function (PDF) of SN magnitude differences $\Delta_M$ predicted by the simulation, so that the predicted number of SNe between $\Delta_M^i$ and $\Delta_M^i + d\Delta_M$ is $NP(\Delta_M^i)d\Delta_M$, where $N$ is the number of observed SNe. Figure 3 shows histograms of the PDF of $\Delta_M$ for $A_V = 0.4$ mag and $M_c = -0.4$. We also plot the observational data of P99. In effect, for this plot, we have brightened the simulated SNe to mimic an $\Omega_m = 1$ model and then dimmed them with dust. We can see that in Figure 3a, where the dust is fairly smoothly distributed, the simulated PDF is not too different from the observations. In the Figures 3b and 3c, which have clumpier dust, there is a skewness, not seen in the observed data, that is due to a long tail of high-extinction lines of sight.

For each set of simulated lines of sight, we form the relative likelihood of drawing all the observed SN magnitudes, $L = \prod_i P(\Delta_M^i)$, where $\Delta_M^i$ is the difference in magnitudes of SN $i$ from a standard candle SN [see (4) above; in the observational sample, this corresponds to the mean of the distribution]. We define the quantity $S = -2 \ln L$ and assume that $S$ follows a $\chi^2$ distribution in order to derive confidence limits on the parameters $M_c$ and $A_V$. In the present analysis, we use results at two different redshifts ($z = 0.05$ and $z = 0.5$) and combine the two by adding the values of $S$. It is this step, combining the likelihoods at two different redshifts, that constrains the amount of additional dispersion (or the change in the shape of the magnitude distribution) that is due to gray dust between low and high redshifts. Contours of $\Delta_S = 2.3$, 6.2, and 11.8 (the difference in $S$ from its minimum value), representing 1 $\sigma$, 2 $\sigma$, and 3 $\sigma$ intervals of joint confidence, are plotted in Figure 4.

Figure 4 shows that the smoothest distribution of dust easily accommodates enough extinction to reconcile a nonaccelerating ($M_c = -0.2$) or flat ($M_c = -0.4$) universe since there is a strong degeneracy between the cosmological magnitude shift and the dust extinction. The other cases, in which dust traces metals and $\rho_d^2$, are quite similar. Such a distribution of dust would be mildly disfavored in a nonaccelerating open universe and ruled out at $\sim 99\%$ confidence in an Einstein–de Sitter universe. The constraints arise mostly because of the shape of the distribution; the fact that the observed dispersions are similar at $z = 0.05$ and $z = 0.5$ is relatively unimportant and only makes a noticeable difference in Figure 4a.

4. DISCUSSION

We have found that current SN data sets appear to have some power to constrain gray dust models. We find it somewhat unlikely (at the $1.5–2 \sigma$ level) that sufficient gray dust could be distributed in the relatively clumpy fashion expected for the metal distribution (e.g., Gnedin & Ostriker 1997; Davé et al. 1998; Cen & Ostriker 1999) to reconcile the P99 data with a nonaccelerating universe. This suggests that any substantial gray dust component must be largely segregated from the galaxies where it was formed. In the specific gray dust model of Aguirre (1999a), sputtering does destroy dust more effectively in denser regions, but once in the IGM, the large grains have long lifetimes, so that dust is still likely to trace the metals. The question of how the dust and metals are distributed can be answered self-consistently by modeling the relevant physical processes (dust and metal ejection from galaxies) directly in the simulations (A. Aguirre et al. 2000, in preparation).

There are many alternative explanations for SNe appearing dimmer in the past. For example, there may be intrinsic SN evolution (Riess et al. 2000a) or even time evolution of the gravitational constant (García-Berro et al. 1999). Such effects would alter the interpretation of our parameter $M_c$. Gravita-
tional lensing magnification (Metcalf 1999) would also change the magnitude dispersion at higher redshifts.

The study we have presented is reasonably general in that our analysis is not dependent on the (unknown) microscopic properties of this hypothetical intergalactic dust. Still, there are some possible systematic uncertainties, which we now consider. We assume (as do P99) that the observed dispersion in SN magnitudes in excess of the estimated observational errors is an intrinsic property of SNe and does not vary with redshift. One could envision scenarios in which the intrinsic dispersion is lower at high redshift, thus allowing more dispersion from dust. However, as mentioned earlier, most of the statistical power of our analysis comes from the shape of the distributions, which is not significantly affected by a change in the intrinsic dispersion. Also, we find that when we decrease the intrinsic SN dispersion (σ_{int}), models with more dust fit slightly better at high z, but the low-z fit becomes worse, a trade-off that means that the overall results hardly change. The distribution shape depends on our assumption that the intrinsic dispersion has a Gaussian distribution in magnitudes, whereas a distribution skewed to fainter magnitudes could weaken our constraints. With a larger sample of low-z SNe, we might be in a position to test this by using the distribution of low-z SN magnitudes to make a simulated high-z sample with the correct intrinsic distribution shape. Also, we have made a simplifying approximation in our simulated high-z samples by using dust extinction magnitudes that result from integrating the dust contribution from z = 0 to exactly z = 0.5. The real SNe are at a range of redshifts; our constraints are effectively conservative because of this. We have also assumed that the total mass of dust does not change with redshift from z = 0.5 to z = 0; dust increasing with time would strengthen our constraints, while a decrease seems implausible. Finally, the truncation of our simulated magnitude distribution at 1 mag is a rather approximate procedure. We have tried changing the cutoff, and we find that with no cutoff (an unrealistic case), the constraints become stronger, as we might expect. With a lower cutoff, the right side of the observed distribution is not reproduced. One additional degree of freedom would involve changing the functional form of the cutoff. In the future, as observations improve, we plan to simulate such observational selection effects more carefully.

On the simulation side, our relatively low mass resolution (m_{min} \approx 8.5 \times 10^{5} M_{\odot}) means that we miss fluctuations in the extinction that occur on smaller mass scales. If we had higher resolution, this should have the effect of making our dust constraints tighter. We find that the dispersion in projected magnitudes largely depends on small-scale fluctuations. We tested this by splitting the simulation into small subvolumes and then shuffling them to remove large-scale correlations (see, e.g., Bhavsar & Ling 1988) before projection, and we obtained similar results. Changing the assumed cosmological model could have some effects, although it is difficult to conceive of models that have less power on small scales while fitting other constraints (see, e.g., White & Croft 2000).

The models of Aguirre (1999a) have grains that do produce some reddening, typically in the infrared. Therefore, a complementary approach to ours would be to use information from different color bands. Such an approach was used by P99, for example, to constrain normal galactic-type dust. Recent near-IR observations by Riess et al. (2000b) have made reddening constraints tight even for nonstandard large dust grains. Our approach does not make any use of color information and therefore constrains the most extreme scenario in which the dust is totally “gray.”

In summary, we have used cosmological hydrodynamic simulations to explore how supernova data can constrain intergalactic gray dust extinction. We conclude that only a fairly smooth distribution of dust could readily mimic the effect of an accelerating universe. Such a distribution would be strange since the dust would be strongly biased away from metal-producing regions. More realistic dust distributions are mildly disfavored, but upcoming samples of SNe (at current redshifts) should enable us to put tighter limits since they determine more precisely the shape of the brightness distribution. At higher redshifts (z \geq 1), the prediction of the gray dust scenario is that SNe should show increased dimming, while decreased dimming would be strong evidence for a cosmological constant.

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REFERENCES

Aguirre, A. 1999a, ApJ, 512, L19
Aguirre, A., & Haiman, Z. 2000, ApJ, 532, 28
Bhavsar, S., & Ling, E. N. 1988, ApJ, 331, L63
Cen, R., Miralda-Escude, J., Ostriker, J. P., & Rauch, M. 1994, ApJ, 437, L9
Cen, R., & Ostriker, J. P. 1999, ApJ, 519, L109
Davé, R., Dubinski, J., & Hernquist, L. 1997, NewA, 2, 277
Davé, R., Hellsten, U., Hernquist, L., Katz, N., & Weinberg, D. H. 1998, ApJ, 509, 661
Davé, R., Hernquist, L., Katz, N., & Weinberg, D. H. 1999, ApJ, 511, 521
García-Berro, E., Gaetzanaga, E., Isern, J., Benvenuto, O., & Althaus, L. 1999, preprint (astro-ph/9907440)
Gnedin, N. Y., & Ostriker, J. P. 1997, ApJ, 486, 581
Hamuy, M., Phillips, M. M., Maza, J., Suntzeff, N. B., Schommer, R. A., & Aviles, R. 1996, AJ, 112, 2391
Hernquist, L., & Katz, N. 1989, ApJS, 70, 419
Hernquist, L., Katz, N., Weinberg, D. H., & Miralda-Escudé, J. 1996, ApJ, 457, L51
Metcalf, R. B. 1999, MNRAS, 305, 746
Perlmutter, S., et al. 1999, ApJ, 517, 565 (P99)
Riess, A. G., et al. 1998, AJ, 116, 1009
Riess, A. G., Filippenko, A. V., Li, W., & Schmidt, B. P. 2000a, ApJ, submitted (astro-ph/9907038)
Riess, A. G., et al. 2000b, ApJ, in press (astro-ph/0001384)
White, M., & Croft, R. A. C. 2000, ApJ, submitted (astro-ph/0001247)