INTERGALACTIC DUST AND THE SUPERNOVA HUBBLE DIAGRAM

ANTHONY N. AGUIRRE
Department of Astronomy, Harvard University
60 Garden St., Cambridge MA, 02138

Type Ia supernovae have been found to be progressively dimmed up to redshift $z \sim 0.7$ relative to the predictions of classic Friedmann solutions with zero cosmological constant. This in turn would require a modification of GR, an exquisitely tuned cosmological constant, or an equally exquisitely tuned negative-pressure contribution to the energy-momentum tensor. A simpler explanation of this dimming – obscuration by a cosmological distribution of dust – violates theoretical constraints derived under two assumptions: that dust is largely confined to galaxies and/or that intergalactic dust would redden visible light in the same way as dust in galaxies. I discuss here the possibility that the selective destruction of very small dust grains by sputtering in the intergalactic medium or during dust removal from galaxies would leave an effectively uniform distribution of non-reddening ('grey') dust that could provide an amount of dimming at $z \sim 0.5$ comparable to the differences in $z \sim 0.5$ theoretical Hubble diagrams.

1 Can dust plausibly account for the dimming?

The supernova data itself places three key constraints on the type of obscuration that could account for the dimming.[1,2,3] (1) It must provide $A_B \approx 0.15 - 0.2$ mag of rest-fame B-band extinction of $z = 0.5$ supernovae to reconcile their fluxes with an open ($\Omega = 0.2$) Friedmann cosmology. (2) The dispersion in flux induced by obscuration must be a sub-dominant component of the total magnitude dispersion observed, since the latter does not increase significantly between low-z and high-z supernova samples.[2] (3) The dust must not induce a systematic change in the mean rest-frame $B - V$ supernova color of $\gtrsim 0.03$ mag, the 1-σ limit obtained by comparing the colors of the $z \sim 0.5$ supernovae with those of supernovae at $z \sim 0.05$.

Dust confined to galactic disks would violate the constraint on dispersion,[1] but for dust outside of galaxies a typical line-of-sight to a supernova may pass through many 'patches' of dust so that the dispersion in supernova magnitudes would be small. The few hydrodynamical simulations which have been performed to track the cosmological distribution of metals outside galaxies show that most metals lie in regions with $\delta \sim 100$, in which case the dispersion would probably be small.[3,4] An analysis using cosmological SPH simulations and an assumed relation between metallicity Z and overdensity δ has shown that the dispersion would be too large if $Z \propto \delta$, but very small for constant metallicity.[5] These are two extremes between which a realistic case would lie.

Several processes through which a galaxy might expell a large fraction of its metal have been discussed in the literature: Supernova winds[6], mergers[7], ram pressure-stripping in clusters[8], and radiation pressure-driven dust efflux.[10,11] Supernova-driven galactic winds are most directly observable, and for these it is found that the winds could expel a cosmologically important level of dust and metals.[9,6] Dust is very likely removed along with gas, but it may be partially destroyed before reaching the IGM: dust removed in wind-entrained outflows and by radiation pressure is subject to sputtering by hot halo gas and in the former case by the wind. Reasonably detailed calculations[10,11] for radiation-pressure ejection show that very small grains, with radii $a \lesssim 0.05$, are completely destroyed, while larger grains are not. Sputtering may also be effective in the lower-density but perhaps high temperature IGM.[3] More generally, it is clear that galactic halos and the hot IGM are hostile environments which will destroy some fraction f of dust. Small grains are preferentially destroyed, but because of the low dust and metal densities outside of galaxies, large-grain shattering or dust formation cannot replenish them. Hence if there is a distribution of grain sizes, the destruction fraction f directly relates to a deficit of very small grains in the grain-size distribution of dust outside galaxies.

To investigate the effect this destruction would have on the properties of dust, it is necessary to assume a model for the grains. Probably the most widely used model of Galactic dust has similar densities of spherical graphite and silicate grains with a grain size distribution $n(a)da \propto a^{-3.5}$ over $0.005\,\mu\mathrm{m} \leq a \lesssim 0.25\,\mu\mathrm{m}$.[12] Among other things, this model successfully accounts the visual opacity ($\kappa_V \approx 4\times 10^4 \mathrm{cm}^2\,\mathrm{g}^{-1}$) and the reddening $R_V \equiv A_V/(A_B - A_V) \simeq 3.1$ typical of dust in the Milky Way. Attenuation of radiation with wavelength $\lambda \gg a$ falls roughly as a/λ; this is why dust reddens. In the the $a^{-3.5}$ grain-size distribution this leads to an interesting situation in which the very small grains dominate the $B-V$ reddening, but larger grains dominate the mass and actually have somewhat higher visual extinction per unit mass. Specifically, calculation of extinction by dust with the truncated distribution $a_{\rm min} \leq a \lesssim 0.25\,\mu\mathrm{m}$, integrated to $z = 0.5$ for a constant comoving dust density and $\Omega = 0.2$, shows that for graphite grains $R_V > 6.2$ for $a_{\rm min} > 0.055\,\mu\mathrm{m}$; the same holds for silicate grains with $a_{\rm min} > 0.15\,\mu\mathrm{m}$, or for an equal-mass graphite/silicate combination if $a_{\rm min} > 0.085\,\mu\mathrm{m}$. These values of $a_{\rm min}$ correspond to dust destruction fractions of $f \gtrsim 0.4$, $f \gtrsim 0.8$ and $f \gtrsim 0.6$ respectively. Such dust is in no way unheard of, as values of $R_V > 6$ have been observed in other galaxies and in dense molecular clouds.[13] Although half as reddening, the visual opacity is $\approx 20\%$ higher ($\kappa \approx 5\times 10^4\,\mathrm{cm}^2\,\mathrm{g}^{-1}$) for the silicate/graphite distribution with $a_{\rm min} = 0.1\,\mu\mathrm{m}$ than for $a_{\rm min} = 0.005\,\mu\mathrm{m}$.

To illustrate the cosmological effect of this type of IG dust, Figure 1 shows the theoretical supernova Hubble diagram for various cosmologies, including an open cosmology with $\Omega_{\rm dust}(z=0) = 4.5\times 10^{-5}$. This model has $a_{\rm min} = 0.1\,\mu\mathrm{m}$, and $\Omega_{\rm dust}(z)$ proportional to the integrated (Madau[14]) star-formation rate. The $z \lesssim 0.7$ overlap of the dust curve and the best Λ-cosmology fit[2] to the supernova data shows that $\Omega_{\rm dust} \approx 4\times 10^{-5}$ is necessary to account for the supernova dimming at $z \sim 0.5$ without cosmic acceleration. With an effective $R_V > 6$, the dust would change the mean $B-V$ supernova color by less than 0.03 mag, as required by the supernova data.

This dust density is compatible with estimates of cosmic metallicity: the following two independent arguments give an expected metal density of $\Omega(Z) \approx (1.5-3)\times 10^{-4}$. First, direct integration of the comoving star-formation rate (SFR) derived[14,15] from observations of both nearby and distant galaxies (at $0.5 \leq z \leq 6$) gives $\Omega_{\rm metals} \approx (1.5-2)h_{65}^{-2}\times 10^{-4}$, assuming a metal-formation rate 1/42 of the SFR. Second, as noted by Renzini, clusters are essentially

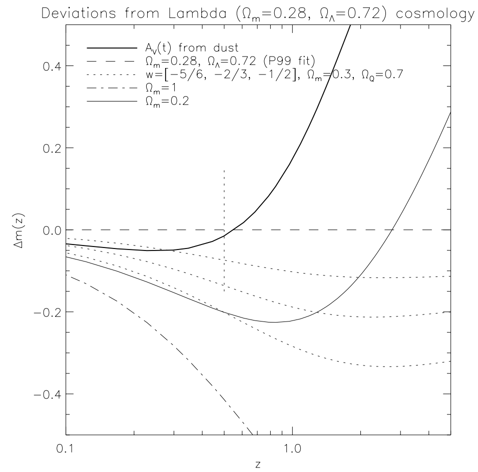

Figure 1: Theoretical Hubble Diagrams. The dust model has $\Omega_{\rm dust}(z=0) = 4.5 \times 10^{-5}$.

closed systems which contain all of the metals produced by their stellar populations.[16] Stars comprise only a fraction $\Upsilon_{\rm cl} \approx 0.09h_{65}^{3/2}$ of the total cluster gas mass, yet the remainder has $\approx 1/3$ solar metallicity. The associated metal production per unit of stellar mass can be written $M_Z \approx M_*[1 + 3.15h_{65}^{-3/2}]Z_\odot$.[16] Unless stars in clusters produce metals much more efficiently than those in field galaxies, this figure should apply to the $\Omega_* \approx 0.004$ of stars in the universe, giving $\Omega_{\rm metals} \approx 3.1\times10^{-4}$. Moreover, if $\Omega_g \approx 0.05$, then the star formation efficiency of clusters well represents that of the universe, $\Upsilon_{\rm IGM} \equiv \frac{\Omega_*}{\Omega_g} \approx \Upsilon_{\rm cl}$, further indicating that clusters are a fair sample. The intracluster gas contains $\approx 75\%$ of all metal in a typical cluster. Since there is no compelling reason to believe that cluster galaxies eject metals much more efficiently than field galaxies do, this fraction should apply also to metals in the IGM.[16] Another way to see this is to note that stars and gas in known galaxies, even of solar metallicity, can hold only $\Omega^{\rm gal}_{\rm metals} = 8 \times 10^{-5}(Z_{\rm gal}/Z_\odot)(\Omega_*/0.004)$, significantly less than the metal estimate from clusters *or* the SFR. Unless both the SFR and cluster arguments and / or the estimate of Ω_* are wrong by a factor of at least two, this indicates that most ($\approx 50-75\%$) cosmic metals reside outside of galaxies even if metal ejection is more efficient in clusters.

Both local galaxies and high-redshift damped Lyman-α absorbing systems show dust / metal ratios of ≈ 0.5.[17] Although radiation pressure could remove dust without gas, it is difficult to remove gaseous metals without dust, so intergalactic dust should have a density $\approx (0.5-1)(1-f) \times (50-75\%)$ that of $\Omega_{\rm metals}$. For $f \approx 0.6$ – corresponding to the absence of $a < 0.1\,\mu$m grains – this yields $\Omega_{\rm dust} \approx (1.5-10)\times10^{-5}$, almost exactly the amount necessary to sufficiently obscure the supernova.

2 How can IG dust be further tested?

The present hypothesis can be tested tested by future supernova results themselves. First, observations of rest R-band colors of $z = 0.5$ supernova should reveal a systematic $B-R$ color change of ≈ 0.1 mag. Second, the magnitudes of supernovae at $z = 1.5$ in a dusty $\Omega = 0.2$ universe diverge from the predictions of an $\Omega = 0.23$, $\Omega_\Lambda = 0.76$ model by ≈ 0.3 mag (see Figure 1), which can be tested once a statistically robust and complete set of $z \gtrsim 1$ supernovae has been observed. The hypothesis that there is a significant mass of IG dust also predicts that all objects at $z \gtrsim 0.5$ should suffer extinction of $0.2 \lesssim A_V \lesssim 1$ mag which is fairly grey out to (observed) $\lambda \approx 0.5(1+z)\,\mu$m. Finally, while calculations show that the dust described here will not significantly distort the CMB spectrum, it would contribute an important component to the observed infrared background.[19]

3 What if the universe 'must be' flat?

The latest CMB anisotropy measurements give strong evidence for a flat universe within the standard inflationary cosmology.[18] Combined with good evidence for low Ω_m, this indicates a negative pressure (i.e. non-clustering) component independent of the supernova data. If this result hols up, does this mean that we can stop worrying about IG dust? Probably not: even if a negative pressure component exists, its nature is completely unknown. The most directly observable property of the 'dark energy' would probably be its equation of state $w = p/\rho$. Figure 1 gives theoretical Hubble diagrams for various values of $w = (const)$, and shows that for a flat universe the current supernova data could be compatible with, for example, *either* a cosmological constant ($w = -1$), *or* quintessence with (constant) $w \lesssim -1/2$ and some intergalactic dust. Since Hubble diagrams are perhaps the most promising way to measure w, correct accounting for possible IG dust remains vital.

4 Conclusions

I would like to leave the reader with three basic points:

1. Several argument strongly suggest that most cosmic metal may well lie *outside* of galaxies.

2. If $\gtrsim 10\%$ of this metal is dust, it would provide extinction to $0.5 \lesssim z \lesssim 1$ comparable to the difference between theoretical Hubble diagrams.

3. There are good reasons to suspect that whatever IG dusts exists may have different properties – particularly in terms of reddening – than 'standard' Galactic dust.

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