Measuring the properties of dust with high-redshift supernovae.

Ariel Goobar, Lars Bergström & Edvard Mörtsell
Fysikum, Stockholm University
e-mail:ariel@physto.se,lbe@physto.se,edvard@physto.se

August 6, 2001

Abstract

Future observations of Type Ia supernovae up to $z \sim 2$, e.g. by the proposed SNAP satellite, will allow the measurement of the properties of dust over cosmological distances. We show that 1% *relative* spectrophotometric accuracy in the wavelength interval 0.7–1.5 μm is required to measure the extinction caused by "grey" dust down to $\delta m = 0.02$ magnitudes in the restframe B-band flux, i.e. the SNAP target limit for systematic uncertainties.

1 Introduction

In this note we investigate the instrumental requirements for the SNAP satellite not to exceed a systematic uncertainty of δm=0.02 mag from dust extinction. More specifically, we concentrate on the relative spectrophotometric accuracy needed to detect the presence of "grey" dust, i.e. a homogeneous intergalactic component with weak differential extinction properties over the restframe optical wavelength regime as described in [1].

Type Ia supernovae form a remarkably homogeneous class of astronomical objects and are therefore well suited for studying the dust properties over cosmological distances. The fraction of scattered/absorbed SN-light in different band-passes is dust model and cosmology dependent as the total extinction at any wavelength depends on the total dust column depth encountered by the photons. This, in turn, depends on cosmological parameters and the assumed density of dust to explain the relative supernova faintness at $z \sim 0.5$. To date, one supernova at $z = 0.46$ for which there exists NIR data has been used to place limits on grey dust [2].

2 Large "grey" dust grains

Following [1], we assume that the intergalactic dust population can be described by a Draine & Lee model [3] where the smaller grains have been destroyed by some unspecified process, plausibly connected to the expulsion of the dust from the star-forming galaxies where the dust originated.

Defining the reddening parameter R_V by

$$A_V = R_V E(B - V),$$

where

$$E(B - V) = (B - V) - (B - V)_i$$

with $(B - V)_i$ being the intrinsic (unobscured) color, a population of large grains may have an R_V parameter as large as 5 to 10, thus giving a uniform ("grey") absorption.

Typically, the most important types of intergalactic grains are silicates and graphite. The optical properties, of which R_V is the most important for our applications, depend to some extent on the actual value chosen for the small-size cutoff $a_{\rm min}$ in the Draine-Lee power-law size distribution. To make contact with [1], we will use $a_{\rm min}$ between 0.08 and 0.12 μm, corresponding roughly to R_V between 5.5 and 9.5. In the numerical calculations, we use the convenient parameterization of the extinction versus wavelength given by [4].

2.1 Extinction by dust at cosmological distances

For a given emission redshift z_e, the attenuation Δm_d at observed wavelength λ_o due to dust can be written

$$\Delta m_d(z_e, \lambda_o) = -2.5 \log_{10} \left[e^{-C \int_0^{z_e} \rho_{\rm dust}(z) a(\lambda_o/(1+z), R_V) h(z) dz} \right], \tag{1}$$

where $\rho_{\rm dust}(z)$ is the physical dust density at redshift z, $a(\lambda, R_V)$ is the wavelength-dependent attenuation ("reddening") parametrized as in [4], and the cosmology-dependent function $h(z)$ is given by

$$h(z) = \frac{1}{H_0\,(1+z)\,\sqrt{(1+z)^2(1+\Omega_M z) - z(2+z)\Omega_\Lambda}}. \tag{2}$$

The normalization constant C is related to the overall magnitude of the extinction, which we fix by demanding that a given cosmology reproduces the observed luminosity distance at $z \sim 0.5$, i.e., that dust extinction can explain the dimming of the presently observed supernova sample, otherwise attributed to the "concordance" cosmology $\Omega_M = 0.3$, $\Omega_\Lambda = 0.7$.

The Monte-Carlo simulation program SNOC [5] was used to perform the integral in (1) numerically by following individual light paths through a large number of cells containing galaxies and intergalactic dust. Through each cell the background cosmology, the wavelength of the photon and the dust density were updated, and the contributions from each cell added. Note that the model is approximately valid also for a patchy dust distribution, as long as the scale of inhomogeneities is small enough, i.e., $1/\sqrt{N} \ll 1$ where N is the number of dust clouds intersected by the light-ray.

In this work we consider the following scenarios:

- Cosmological parameters: $(\Omega_M, \Omega_\Lambda) = (0.3, 0.7)$.
- R_V ranging from 5.5 to 9.5, constant in the interval $0 < z < 2$.

- $\rho_{\rm dust} = \rho^{\circ}_{\rm dust}(1+z)^{\alpha}$, where

$$\alpha(z) = \begin{cases} 3 \text{ for all } z & \text{Model A} \\ 0 \text{ for } z > 0.5 \text{ (3 for lower } z) & \text{Model B} \end{cases}$$

  i.e. Model B implies that

$$\rho_{\rm dust}(z > 0.5) = \rho_{\rm dust}(z = 0.5) = \text{ constant},$$

  so the comoving density increases with cosmic time until $z = 0.5$ from which it is constant.

- The extinction scale-length, i.e., the interaction length for photon scattering with dust particles, $\lambda \propto (\sigma \cdot \rho^{\circ}_{\rm dust})^{-1}$ is in the range (5 - 300)$\cdot \left(\frac{h}{0.65}\right)$ Gpc, where σ is the interaction cross-section.

Although neither model A nor B is necessarily very plausible, they serve as useful limiting cases for more natural scenarios where the dust density is generated and distributed over a finite time scale.

2.2 Spectrophotometry in the presence of dust

In order to quantify the induced differential spectral shift due to large dust grains we introduce two quantities: R_1 is the magnitude difference in extinction between λ=0.7 and 1.0 μm. R_2 measures the differential extinction between λ=0.7 and 1.5 μm, as shown in Figure 1 for a source at $z = 1$. Also shown in the Figure is a fit of a fifth order polynomial over the wavelength range $\lambda = 0.4$ to 1.7 μm.

The rationale for introducing R_1 and R_2 is twofold: 1) the color dependence is almost linear in the range between λ=0.7 and 1.5 μm. 2) R_1 and R_2 can be measured within the sensitive range of an infrared (HgCdTe) detector. R_1 can *also* be measured with a CCD detector.

3 Grey dust simulations

We consider the scenario where the extinction due to dust is negligible at $z \sim 0.5$ but that it may introduce a bias in the Hubble diagram in excess of δm=0.02 for $z \leq 2$. Figures 2 and 3 show a case in dust model A. At the limiting redshift range of SNAP a 0.1 magnitude bias in the Hubble diagram results in approximately a 6% differential reddening for R_2 and 2% in R_1 for R_V=5.5. For the same scenario but with R_V=9.5 the best discrimination can be done for $z \gtrsim 0.8$, leading to a 0.015-0.02 magnitude differential reddening as defined by R_2. The corresponding situation with a saturated dust density (model B) can be seen in figures 4 and 5.

The "greyness" of r>100 nm dust grains make them completely undetectable with colors bluer than R-band in the restframe system. However, for longer wavelengths the extinction leaves a measurable signature in the observed V-J,R-J and I-J. This indicates that the *average* V-J, R-J and I-J colors of *normal* Type Ia supernovae are significantly different with and without the extinction due to large dust grains.

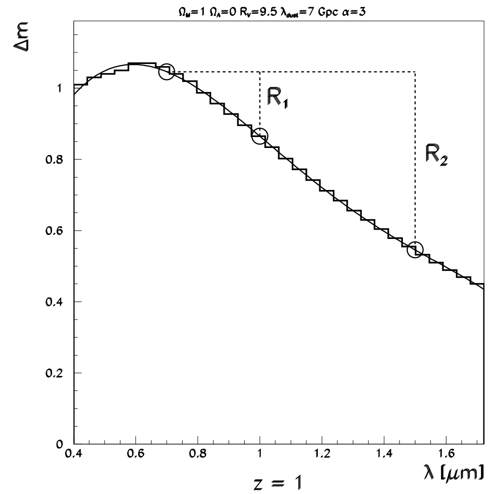

Figure 1: Monte-Carlo simulation of the differential extinction between $\lambda = 0.4$ and 1.7 μm for a source at a redshift $z = 1$. The solid line shows a fit to a fifth order polynomial. R_1 is defined to be the magnitude difference in extinction between 0.7 μm and 1.0 μm. R_2 measures the differential extinction between 0.7 μm and 1.5 μm.

4 Discussion

The effects of grey dust extinction capable of biasing the results of experiments such as the proposed SNAP satellite can be diagnosed through accurate relative spectrophotometry at the 1% level in the 0.7-1.5 μm wavelength range. This would allow testing grey dust obscuration affecting the measurement of high-z supernovae up to $\Delta m \sim 0.02$, the target for systematic uncertainties for SNAP.

In the meantime, significant progress in examining the possible bias of grey dust in the interpretation of $z \sim 0.5$ supernovae with NIR data. If the faintness of Type Ia SNe at z$\sim$0.5 is to be attributed to grey dust obscuration as opposed to the cosmological explanation, $\gtrsim$0.05 magnitudes of extinction in e.g. R-J would result. Testing this possibility is within reach with ground based facilities.

References

[1] A. Aguirre, Astrophys. J. **525** (1999) 583; A. Aguirre and Z. Haiman, Astrophys. J. **532** (2000) 28.

[2] A. Riess *et al.*, ApJ, 536, 62 (2000).

[3] B. Draine and H. Lee, Astrophys. J. **285** (1984) 89.

[4] J.A. Cardelli, G.C. Clayton and J.S. Mathis, Astrophys. J. **345** (1989) 245.

[5] The SNOC simulation package, A. Goobar et. al.

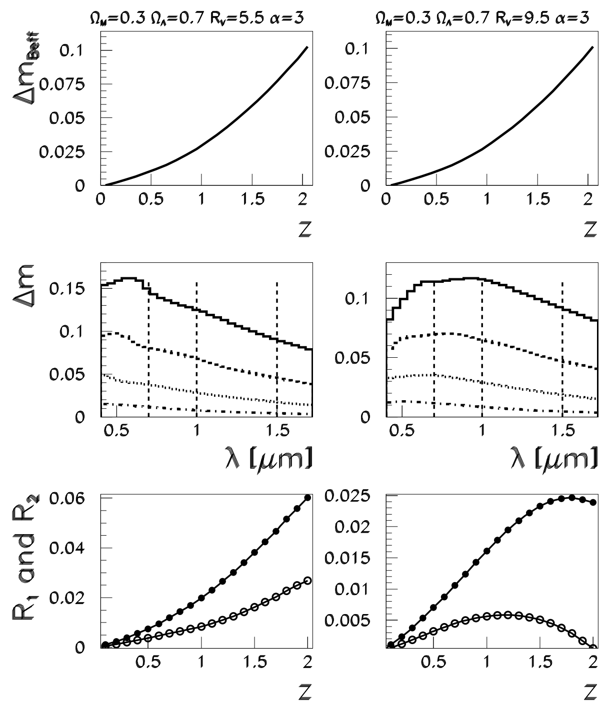

Figure 2: Dust extinction in model A for R_V=5.5 (left side) and R_V=9.5 (right side) in a flat Λ-dominated universe with the dust density adjusted to generate about 0.1 mag dimming in the observed band corresponding to the restframe B-band magnitude from a source at the limiting SNAP depth ($\lambda_{\rm dust}$=300$\cdot\left(\frac{0.65}{h}\right)$ Gpc). The upper panels show the dimming in the observational band corresponding to the restframe B-band. The middle panels show the differential extinction as a function of wavelength for a source at redshifts $z = 0.5, 1.0, 1.5$ and 2.0. The dashed lines show the position of λ= 0.7, 1.0 and 1.5 μm used to calculate R_1 and R_2. The bottom panels show the differential color coefficients R_1 and R_2 as a function of redshift.

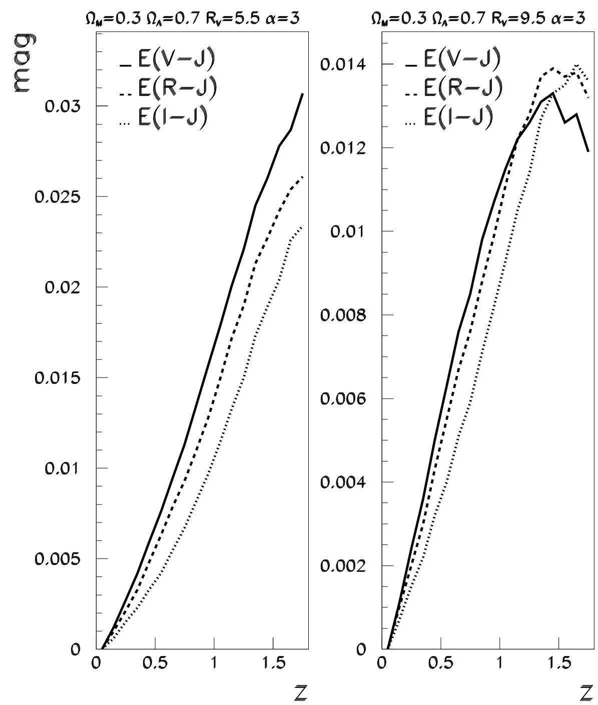

Figure 3: Color extinctions E(V-J),E(R-J) and E(I-J) for Type Ia supernovae in dust model A for R_V=5.5 (left side) and R_V=9.5 (right side) in a flat Λ-dominated universe with the dust density adjusted to generate about 0.1 mag dimming in the observed band corresponding to the restframe B-band magnitude from a source at the limiting SNAP depth.

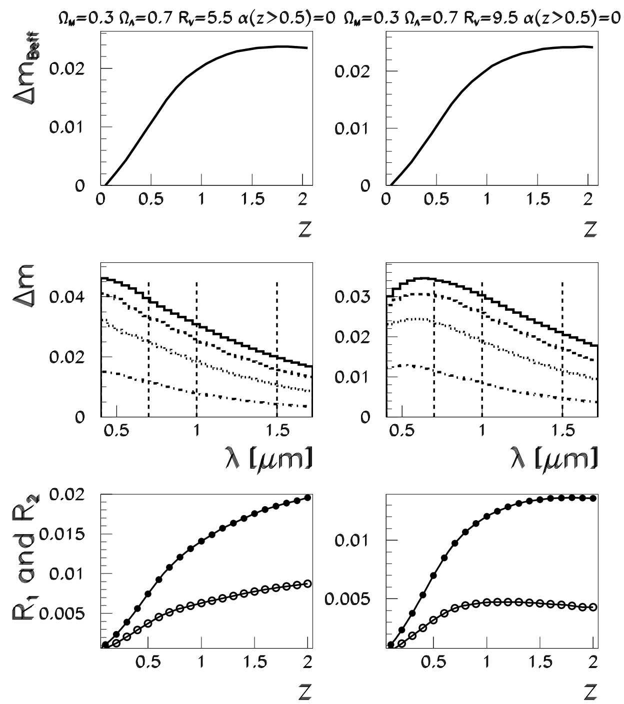

Figure 4: Dust extinction in model B for R_V=5.5 (left side) and R_V=9.5 (right side) in a flat Λ-dominated universe with the dust density adjusted to generate about 0.02 mag dimming in the observed band corresponding to the restframe B-band magnitude from a source at the limiting SNAP depth ($\lambda_{\rm dust}$=300$\cdot \left(\frac{0.65}{h}\right)$ Gpc). The upper panels show the dimming in the observational band corresponding to the restframe B-band. The middle panels show the differential extinction as a function of wavelength for a source at redshifts $z = 0.5, 1.0, 1.5$ and 2.0. The dashed lines show the position of λ= 0.7, 1.0 and 1.5 μm used to calculate R_1 and R_2. The bottom panels show the differential color coefficients R_1 and R_2 as a function of redshift.

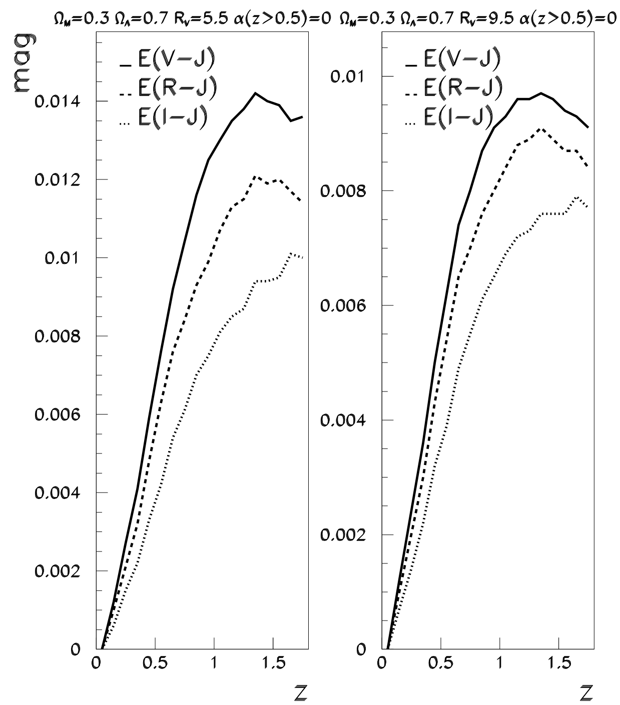

Figure 5: Color extinctions E(V-J),E(R-J) and E(I-J) for Type Ia supernovae in dust model B for R_V=5.5 (left side) and R_V=9.5 (right side) in a flat Λ-dominated universe with the dust density adjusted to generate about 0.02 mag dimming in the observed band corresponding to the restframe B-band magnitude from a source at the limiting SNAP depth.