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ORIGINAL ARTICLE

Apparent magnitudes of high redshift Type 1a supernovae and intergalactic graphite whiskers

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Abstract The concept of a Universe undergoing an acceleration in its expansion rate and predicating the existence of dark energy is based on observed deficits in brightness of Type 1a supernovae at high redshifts, amounting to Δ m ∼ 0.3–0.5. We show that the effect of intergalactic graphite whiskers of radii in the general range 0.03–0.07 µm and lengths in excess of ∼5 µm will be to mimic the effects of dark energy in the redshift magnitude relation for Type 1a supernovae. The mean intergalactic density of whiskers required for such an effect is $\sim 3 \times 10^{-34}$ g cm^{-3}, about 10^{-5} of the critical closure density.

Keywords Cosmology · Dark energy · Type 1a supernovae · Graphite whiskers · Intergalactic dust

1 Introduction

The observations of distant Type 1a supernovae caused by the explosions of degenerate dwarf stars (SNe) (Riess et al. 1998; Perlmutter et al. 1999) have been widely regarded as confirmation of a 'dark energy' component in the energy density of the Universe. Since the absolute luminosities of SNe in nearby low-redshift galaxies can be established as invariant to a high degree, this important class of astronomical object could serve as 'standard candles' in red-shift magnitude diagrams. Such Hubble diagrams based on SNe data have shown a deficit of brightness at high redshifts which is interpreted as due to acceleration of the expansion rate of the Universe.

Defining

$$\rho_c = 3H_0^2 c/8\pi G \quad (1)$$

to be the critical density of the Universe, and setting $\Omega = \rho/\rho_c = 1$, with Ω distributed between luminous matter and cold dark matter (M) and dark energy (Λ), we have

$$\Omega = \Omega_M + \Omega_\Lambda \quad (2)$$

Figure 1 shows the result of a compilation of SNe data by Astier et al. (2006). The data evidently distinguishes between the two classes of theoretical model $(\Omega_M, \Omega_\Lambda) = (0.26, 0.74)$ and $(\Omega_M, \Omega_\Lambda) = (1.0, 0.0)$, the former requiring the presence of dark energy. Comparing the two models with the data points we see that a discrepancy for the case $(\Omega_M, \Omega_\Lambda) = (1.0, 0.0)$ amounting to a difference of Δ m = 0.2–0.5 mag for z in the range 0.3–1.

More recent HST observations have extended the Hubble relation for Type 1a SNe's to redshifts $z \sim 2$ (Riess et al. 2007). A mean SNe Hubble relation derived from combining data of Astier et al. (2006) and Riess et al. (2007) is represented by the connected points in Fig. 2. The dashed curve is the prediction for a standard cosmology $(\Omega_M, \Omega_\Lambda) = (1.0, 0.0)$ where the discrepancy is now seen to extend to $z \sim 1.8$. It is precisely this discrepancy that provides a major strut to the hypothesis of dark energy and a Universe with an accelerating rate of expansion.

Several effects that might rectify this discrepancy within the framework of non-dark energy cosmologies have been discussed in the literature and dismissed as being insignificant (Leibundgut 2001; Sullivan et al. 2003). Extinction by dust has been considered, both for dust within our galaxy and in the host galaxy in which the SNe resides on the assumption that the dust has similar properties to interstellar

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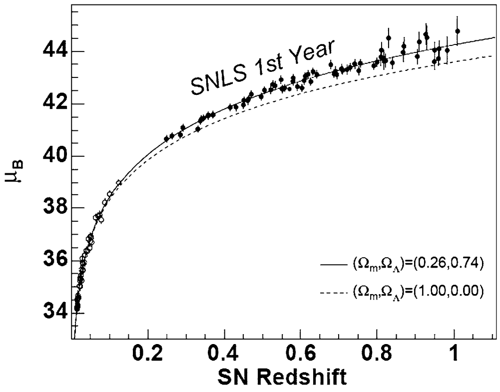


Fig. 1 Hubble diagram for supernovae compared with models from Astier et al. (2006)

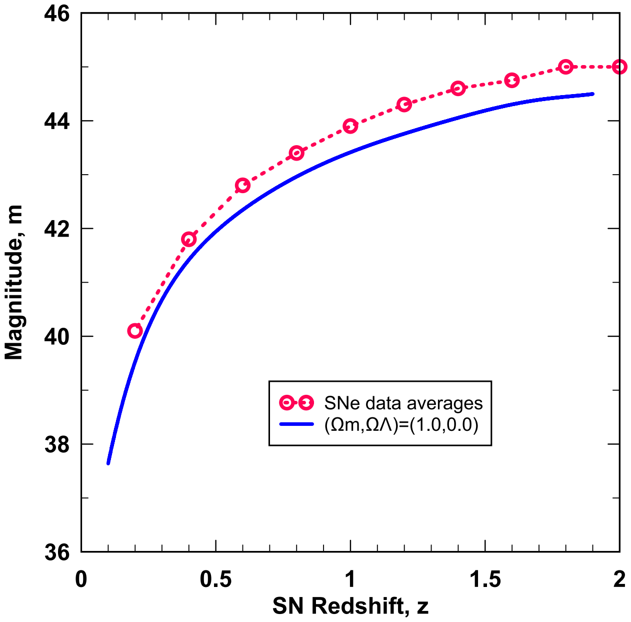


Fig. 2 Hubble diagram for supernovae compared with models from Astier et al. (2006) and Reiss et al. (2007)

dust. With these assumptions the contribution of dust to supernova magnitudes has been claimed to be negligible.

The possibility of dust producing gray (wavelength independent) extinction over the relevant waveband has also been discussed by Croft et al. (2000) and Aguirre (1999) and dismissed as admissible on the grounds that such dust had to be distributed outside host galaxies, a situation that was thought untenable. The presence of intergalactic dust cannot be ruled out, however. With $H_0 = 71$ km/s Mpc^{-1}, $\rho_c = 10^{-29}$ g cm^{-3}, and a baryonic density established by stellar nucleosynthesis of $\sim 4 \times 10^{-31}$ g cm^{-3}, an intergalactic dust density of $\rho_{\mathrm{dust}} = (3\text{–}5) \times 10^{-34}$ (comprised of graphite, say) would be entirely plausible.

2 Graphite whiskers

Hoyle and Wickramasinghe (1970) first proposed that graphite particles could be formed and expelled in supernova explosions, and Edmunds and Wickramasinghe (1975) discussed their possible astrophysical role if they condensed in the form of slender whiskers.

Whiskers comprised of either iron or graphite, condensed in supernova ejecta can be expelled at speeds of $\sim 10^5$ cm/s and eventually escape entirely from the galaxies in which they are produced (Hoyle and Wickramasinghe 1988; Chiao and Wickramasinghe 1972). Intergalactic space (in late epochs) would then be populated by whisker grains of radii typically <0.05 μm and lengths in excess of several μm. The density of such whiskers could build up to a significant fraction of the C produced by stellar nucleosynthesis. A density of $\sim 3 \times 10^{-34}$ g cm^{-3}, <0.03 percent of ρ_c is thus easy to defend on this basis (Hoyle et al. 2000; Banerjee et al. 2000).

The recent discovery of graphite whiskers in CV-type carbonaceous chondrites (Fries and Steele 2008) gives credence to the notion that their distribution in the cosmos may be widespread. The structures identified by Fries and Steele (2008) have diameters ~ 0.1 μm and lengths of several μm. Since the Type 1a SNe light curves peak in the visual/near UV spectral region in their co-moving frames, objects redshifted to $z = 0.5\text{–}2$ would encounter intergalactic dust at wavelengths redshifted into the near IR. The dimming of supernovae due to such whiskers may then be modelled using Mie-type formulae for cylinders (Wickramasinghe 1973).

3 The effect of intergalactic graphite whiskers

To calculate the effect of intergalactic graphite whiskers it is first necessary to calculate $\kappa(\lambda)$, the mass extinction coefficient for a whisker of given radius. Treating a whisker as a homogeneous infinite cylinder with radius a, its extinction efficiencies can be calculated from formulae (Bohren and Huffman 1983; Wickramasinghe 1973; Van de Hulst 1957) for which computer routines are readily available. The optical constants needed for these calculations were taken from tabulations by Taft and Philipp (1965) and Hoyle and Wickramasinghe (1991).

The average extinction efficiency of a set of randomly oriented graphite whiskers of radius a, length 1 is then given by

$$\langle Q \rangle = (2Q_{eH} + Q_{eE})/3 \tag{3}$$

where Q_{eH}, Q_{eE} refer respectively to efficiency factors for light with electric and magnetic vectors parallel to the cylinder axis. Since $2al$ is the projected geometrical area of a cylinder and $\pi a^2\, ls$ is the mass, where s is the density of

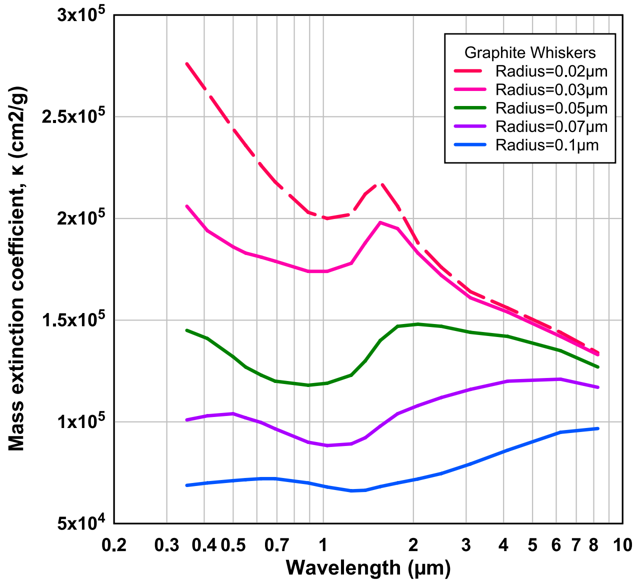


Fig. 3 Mass extinction coefficient for infinite graphite cylinders of various radii

graphite (=2.2 g cm^{-3}), the mean mass extinction coefficient is

$$\kappa(\lambda, a) = 2al\langle Q\rangle/\pi a^2 s \tag{4}$$

Figure 3 shows plots of $\kappa(\lambda, a)$ for various values of a. These calculations (infinite cylinder approximation) are valid for cylinders with lengths significantly in excess of $\lambda/2\pi$, a condition that is adequately met in the present application. A procedure to deal with far infrared wavelengths developed by Wickramasinghe and Wallis (1996) will not be required in this instance.

4 SNe Hubble diagram and graphite whiskers

We now explore the effect of intergalactic graphite whiskers with mass extinction $\kappa(\lambda, a)$ defined by (4) and Fig. 3 in causing attenuation of light from a supernova at redshift z_0. The attenuation in magnitudes has then to be added to the $m(z)$ function (dashed curve) in Fig. 2 to compute the final magnitude-redshift relation for Type 1a Supernovae. For the purpose of this computation we consider a cosmological model with $k = 0$ (Einstein-de Sitter metric) and zero cosmological constant.

$$ds^2 = c^2dt^2 - S^2(t)[dr^2 + r^2(d\theta^2 + \sin^2\theta d\phi^2)] \tag{5}$$

where $S(t)$ is the scale factor, and $H(t)$ the Hubble constant and $q(t)$ the deceleration are defined at any epoch t by

$$H(t) = (1/S)dS/dt; \qquad q(t) = -(1/H^2S^2)dS/dt \tag{6}$$

For simplicity we consider SNe to be monochromatic emitters at wavelength λ_{em} in their rest frame, with typical value $\lambda_{\text{em}} = 0.5$ µm.

If q_0 and H_0 represent the values of H and q (6) at the present epoch the optical depth to a particular Type 1a supernova at redshift z_0 is given by (e.g. Weinberg 1972)

$$\tau(z_0) = \frac{c}{H_0}\int_0^{z_0} \kappa\left(\frac{\lambda_0}{1+z}\right)\rho(z)\frac{dz}{(1+z)^2\sqrt{1+2q_0z}} \tag{7}$$

Here $\rho(z)$ is the smeared-out mass density of graphite whiskers and the wavelength of the rest-frame emission from the supernova is

$$\lambda_{\text{em}} = \lambda_0/(1+z) \tag{8}$$

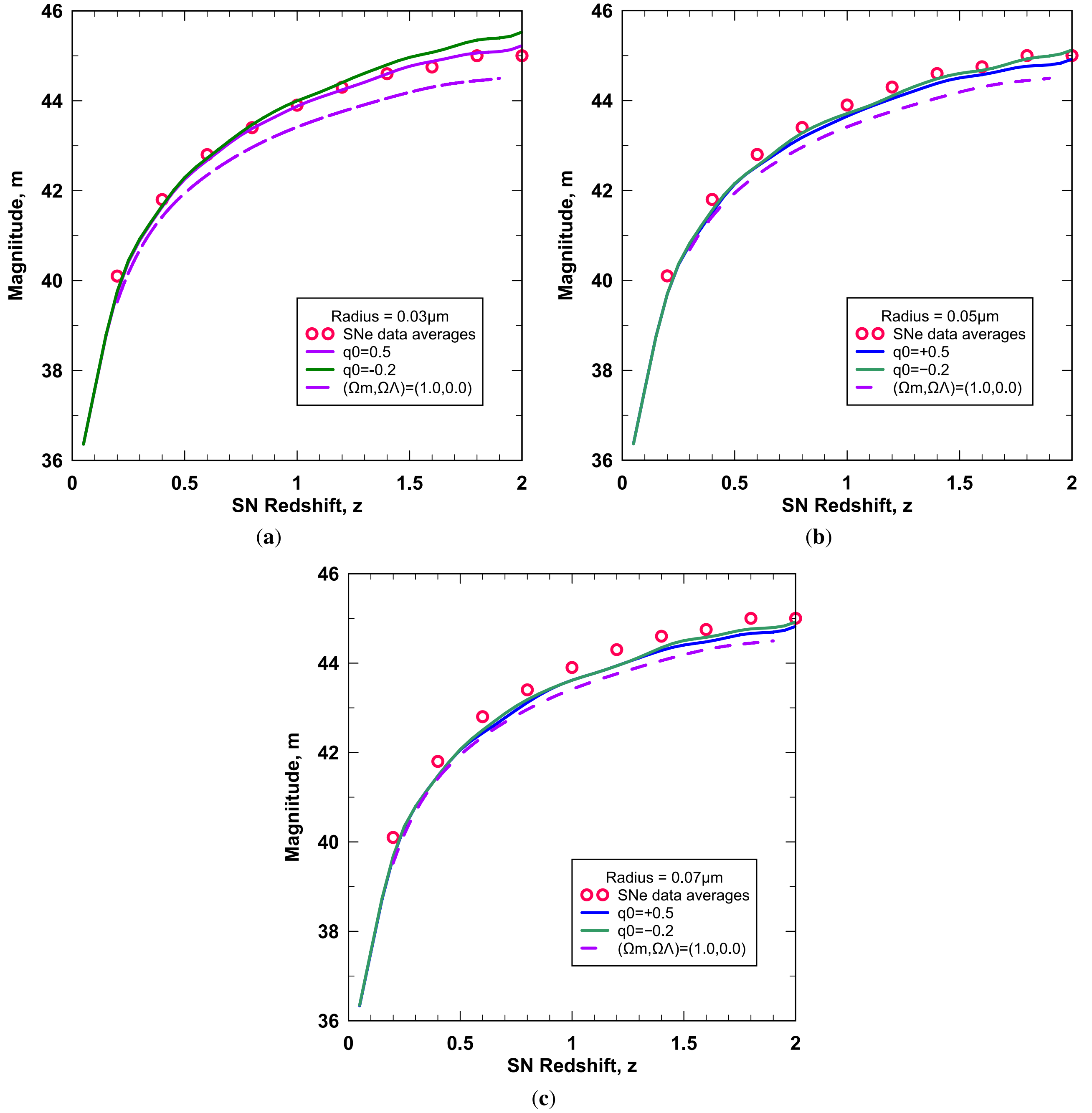
Assuming the smeared out density of graphite whiskers to have reached a more or less constant value of ρ_0 at later (recent) cosmological epochs

$$\tau(z_0) = \frac{c}{H_0}\rho_0\int_0^{z_0} \kappa\left(\frac{\lambda_0}{1+z}\right)\frac{dz}{(1+z)^2\sqrt{1+2q_0z}} \tag{9}$$

For prescribed values of z_0. ρ and q_0, H_0, together with $\kappa(\lambda, a)$ calculated earlier, the integral (9) can be computed numerically. We adopt a value of $H_0 = 71$ km/s Mpc^{-1} and consider the separate cases of $q_0 = -0.2, 0, +0.5$ to span a range of values of the deceleration parameter currently considered to be reasonable (Freedman and Turner 2003). The final Hubble relation is calculated from the equation

$$m(z_0) = m_0(z_0) + \tau(z_0) \tag{10}$$

Here $m_0(\text{z}_0)$ is the Hubble relation for a non-dark-energy cosmological model as defined by the dashed curve in Fig. 2. The results of the computed $m(z_0)$ for whiskers of radii $a = 0.03$, 0.05 and 0.07 µm are plotted in Figs. 4a, b, c, adopting a smeared-out intergalactic density of graphite whiskers to be $\rho_0 = 3 \times 10^{-34}$ g cm^{-3}. This value is considered to be within reasonable limits for the density of intergalactic carbon at recent epochs (Hoyle et al. 2000). We note from (9) that the values of optical depth simply scales with ρ_0. Figure 4 shows that graphite whiskers of radii $a = 0.03$, 0.05 µm come very close to matching the observational data for Type 1a supernovae, with the adopted value of ρ_0. An increase in the value of ρ_0 by a factor ∼2 gives a similarly good correspondence with the data for the case $a = 0.07$ µm. Neither of these values of ρ_0 can be considered unreasonable for the notional intergalactic density of graphite whiskers. Whiskers with radii 0.03–0.05 µm which are more efficient absorbers (see Fig. 3) might be considered preferable if the density of C is regarded as a severe constraint, whilst larger particles of radii 0.05–0.07 µm might be preferable if intergalactic reddening is to be kept to a minimum.



(**a**) (**b**) (**c**)

Fig. 4 SNe Hubble relation for graphite whiskers of radii (**a**) 0.03 μm, (**b**) 0.05 μm, (**c**) 0.07 μm, calculated for flat cosmologies with $\Omega_\Lambda = 0.0$, and various values of q_0

5 Discussion

Recent studies of the Hubble relation for Type 1a supernovae have shown that supernovae at redshifts in the range 0.3–2 are systematically dimmer than would be expected for cosmological models that have only gravitational deceleration from matter. The discrepancy, shown in Figs. 1 and 2, is conventionally explained as evidence for a Universe with an accelerating rate of expansion. The acceleration is achieved by introducing a cosmological constant in the field equations, which in turn leads to the identification of 'dark energy'.

The recent discovery of graphite whiskers in CV carbonaceous meteorites (Fries and Steele 2008) provides direct evidence for astronomical prevalence of such whiskers, supporting earlier theoretical arguments that they could form in supernova ejecta and be expelled into interstellar clouds and eventually into intergalactic space. The new laboratory discovery prompted us to explore these arguments further, re-examining the proposition that intergalactic matter includes a component in the form of graphite whiskers that can produce absorption/extinction effects at optical and infrared wavelengths. Figure 4 shows that the Hubble relationship for Type 1a supernovae could have an alternative explanation within the framework of cosmologies without invoking dark energy, if intergalactic whiskers exist. For whiskers with radii in the range 0.03–0.07 μm we find that a mean intergalactic density of $\sim 3 \times 10^{-34}$ g cm^{-3} would mimic the effects of dark energy in the magnitude-redshift relation of Type 1a supernovae. Although other arguments can be brought to bear on the assertion of 'dark energy', the SNe data taken alone might turn out to be insecure, or equivocal at best.

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