Dust around Type Ia supernovae

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ABSTRACT

An explanation is given of the low value of $R_\lambda \equiv A_\lambda/E(B-V)$, the ratio of absolute to selective extinction deduced from Type Ia supernova observations. The idea involves scattering by dust clouds located in the circumstellar environment, or at the highest velocity shells of the supernova ejecta. The scattered light tends to reduce the effective R_λ in the optical, but has an opposite effect in the ultraviolet. The presence of circumstellar dust can be tested by ultraviolet to near infrared observations and by multi-epoch spectropolarimetry of SNe Ia.

Subject headings: Supernovae: General, Dust, Extinction

1. Introduction

Dust extinction of SNe Ia is of critical importance to supernova cosmology. New studies show that when correcting the observed B magnitudes of SNe Ia to the observed $B-V$ colors, the coefficient is generally found to be around 2-3 instead of the value of about $R_B \equiv A_B/E(B-V) = 4.1$ as expected for dust extinction in the Galaxy and the LMC (Tripp & Branch 1999; Phillips et al. 1999; Wang et al. 2003; Knop et al. 2003; Wang et al. 2005). This small value is likely caused by a combination of intrinsic color dependence of SN luminosity and dust extinction. Some recent works however show that for several well observed highly extinct SNe Ia, R_B were found to be in the same range as deduced from cosmology fits (*e.g.* Krisciunas et al. (2001, 2004)). These studies seem to suggest that dust in SN hosts are systematically different from those in the Galaxy and the LMC. Here I propose an alternative explanation that does not require such a difference.

2. The circumstellar dust of SNe Ia

There might be circumstellar (CS) dust around the progenitor systems of SNe Ia. In such cases extinction correction can not be performed by assuming a standard interstellar

extinction law, but has to be treated through careful radiative transfer (Witt et al. 1992). SN 2002ic, as an extreme example, was found to be associated with a massive hydrogen rich material with mass around $6M\odot/(n/10^8 cm^3)$ (Hamuy et al. 2003; Wang et al. 2004; Wood-Vasey et al. 2004; Deng et al. 2004). Wang et al. (2004) deduced from spectropolarimetry observations that the hydrogen rich materials are distributed in an asymmetric, perhaps disk-like geometry. Such a massive envelope, if exists in the Galaxy, must be easily observable. It can in fact be identified with well studied post-AGB objects such as proto-planetary nebulae (PPNe). The post-AGB phase is very short lived, lasting only on the order of a few thousand years. This explains why SN 2002ic like events are rare but it also raises the question of whether SNe Ia can occur in environment in which the surrounding nebulosity is more diluted. PPNe ultimately evolve to planetary nebulae (PNe) which then disperse into the interstellar medium (ISM) and leave behind white dwarfs in the center. A large fraction of white dwarfs inside PNe are found to be likely in binary systems (De Marco et al. 2004). The PN phase lasts for about ten to a hundred times longer than the PPN phase. Assuming that the explosion of the central white dwarfs are unrelated to the evolution of nebulosity outside, one can expect that there are about 10 times more SNe Ia occurring inside PNe for every SN Ia occurring inside a PPN. Extinction to the central white dwarfs of several PNe were observed by Wolff et al. (2000), and the dust extinction optical depth is typically around 1. Assuming that there is no dust creation/destruction after the PPN shell ejection and homologous expansion of the nebulae, at any later epochs the dust opacity scales as $\frac{\tau_B}{1}(\frac{10000 \text{year}}{t})^2$, where t is the dynamical age of PNe which is typically around 10,000 years. It thus takes about 10^5 years for the dust to be diluted to $\tau < 0.01$ - a level that is still sensitive to modern SNe Ia observations. Dusts in PNe are distributed in patchy opaque clumps such as observed in the Helix nebula (O'Dell et al. 2004). These dusty clumps may survive even longer time scales. On top of the dust ejected as PPNe during the post-AGB phase, more dust may be ejected to the CS environment throughout the evolution path to SNe Ia. This argues that circumstellar dust may be important and has to be analyzed carefully for precision measurements.

3.   Dust scattering and absorptions

The albedo of interstellar dust is around 0.7 in B and V filters, as was found from observations of reflection nebulae (see Draine (2003) for a review of interstellar dust properties). This means that scattering dominates the interaction between photons and dust particles.

3.1. The case of time invariable sources

For illustrative purposes, let us consider an invariant point source located inside a optically thin CS shell of optical depth $\tau \ll 1$ and albedo ω. In one extreme case (Case A, hereafter) we assume that all the scattered photons do not reach the observer, then the attenuation of the source is given by $e^{-\tau}$. Case A applies to interstellar dust extinction where scattering predominantly direct photons off the line of sights. If on the other extreme (Case B, hereafter) we assume that all of the scattered photons eventually escape from the system, the corresponding attenuation will be $e^{-\tau \cdot (1-\omega)}$, where it is also assumed that each photon interacts at most once with the dust shell before escape which is a good approximation if the shell is optically thin. Case B alters the extinction curves of the dust from A_λ to $A_\lambda^0 = A_\lambda(1 - \omega(\lambda))$. A complete description of the amount of extinction requires not only the extinction cross section but also the dust albedo. Using the interstellar dust model of Weingartner & Draine (2001) for the average properties of LMC dust, the two limiting cases are shown in Fig. 1. The inclusion of scattered photons not only reduces the total extinction but also changes significantly $R_\lambda \equiv A_\lambda/E(B-V)$, the ratio of extinction to color-excess. R_λ is significantly reduced at wavelength longer than 300 nm whereas the opposite is true in the wavelength range shorter than 300 nm.

Case A is applicable for extinction by interstellar dust. Case B is applicable for extinction by a dust envelopes that can not be spatially resolved from the target, such as compact CS dust of stars or circumnuclear dust in the host galaxies of AGNs or QSOs.

3.2. The dependence of dust attenuation on the spectral evolution of SN Ia

The light curves and spectra of SNe evolve with time. The effective wavelengths in different filters thus vary, and accordingly the amount of extinctions in these filters change with time. Using the dust model of Weingartner & Draine (2001), and the SN Ia spectral template as described in Knop et al. (2003), we show in Fig. 2(a) R_λ at different epochs for a typical SN Ia. R_λ show $\sim 20\%$ variations. This effect should be important when using SN Ia for cosmology, but can not explain the observed low R_B for SNe Ia.

3.3. The time dependency of dust scattering

Light reflected off dust particles travels longer distance and arrives at the observer with a time delay. This is the so called light echo phenomena studied by Chevalier (1986), and more recently by Sugerman (2003) and Patat (2005). Light echos are observed in several nearby
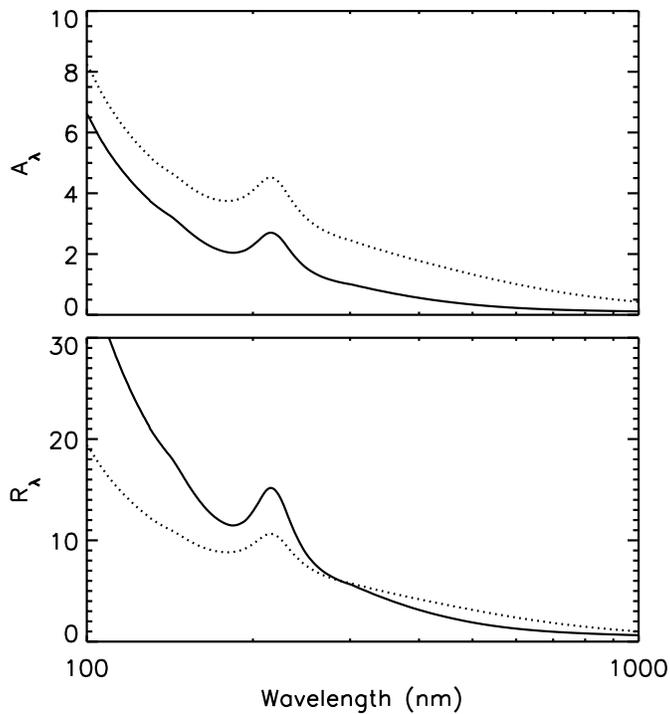
Fig. 1.— The extinction properties of the dust model of Weingartner & Draine (2001) for the LMC average. The dotted lines show the the total extinction (a, upper panel) and the ratio of total extinction to E(B-V) (b, lower panel) if scattered photons are all unobservable (Case A, see text). The solid lines show the corresponding quantities assuming single photo-dust interaction and all scattered photons escape from the dust shell and are observable (Case B, see text). The extinction curves are dramatically different for Case A and Case B.
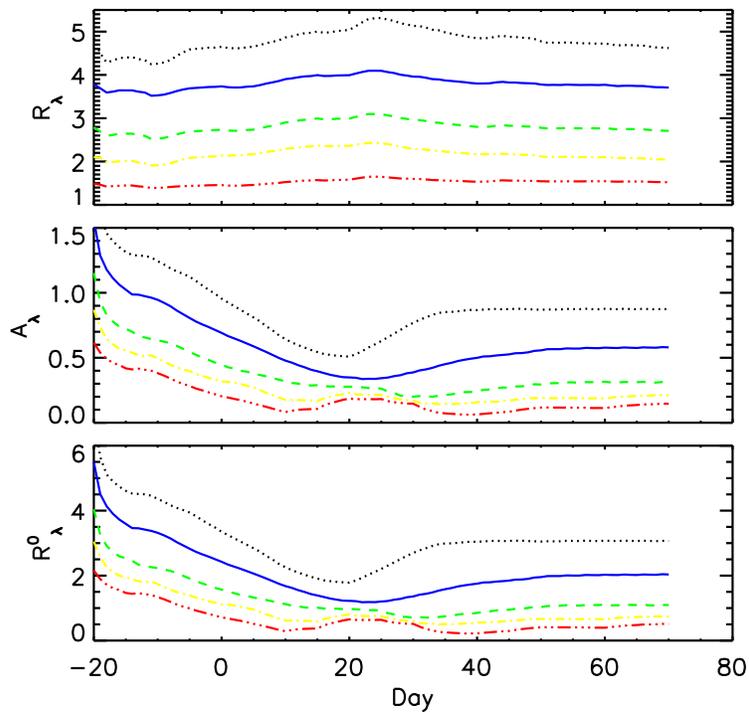
Fig. 2.— The time dependence of extinction properties in U (dotted line), B (solid line), V (dashed line), R (dot-dashed line), and I (dot-dot-dot-dashed line) bands for Type Ia supernovae. (a), upper panel, shows the effect on R_λ due to spectral time evolution. (b), middle panel, and (c), lower panel, show the A_λ and R_λ^0 as defined in §3.3, respectively. The curves in (b) and (c) were derived assuming a spherically symmetric distribution of dust at a radius above $1\ 10^{16}$ cm and an optical depth of 1.45 in B band.

SNe such as SN 1987A (Crotts et al. 1989; Sugerman et al. 2005), SN 1991T (Schmidt et al. 1994), and SN 1998bu (Cappellaro et al. 2001). The survival of CS dust around SN 1987A was studied by Wang & Wheeler (1996) where it was shown that scattering by circumstellar dust can provide an alternative explanation of early polarimetry of SN 1987A. Wang et al. (1996) also suggest that dust around SNe Ia can be probed by polarimetry observations.

The exact amount of extinction is related to the geometric location of the dust clouds. In Fig. 2(b) and (c) we show as an example the results assuming a geometry in which dust coexists with a stellar wind of inner radius $1\ 10^{16}$ cm. The optical depth of the dust cloud is assumed to be 1.45 in B band which gives $A_B = 1.34\ mag$. The effect of multiple scattering is treated approximately using the formula of Mathis (1972). With the extinction cross section as given by Weingartner & Draine (2001) for dust in the LMC, the column density of the dust shell considered here is 10^{22} cm^{-2} which requires a mass loss rate of $3.3\cdot10^{-5}$M $\odot$ /year.

As shown in Fig. 2(b), the extinctions in different filters decrease steadily from the time of explosion to about 15-20 days after optical maximum. This is due to an increase of the contributions of scattered photons to the total flux. The effective extinction is in general smaller than when dust scattering is ignored. Fig. 2(c) shows the effective ratio of extinction to color-excess. To be consistent with SN Ia observations, this is defined here as $R_\lambda^0 = A_\lambda/E^0(B-V)$, with $E^0(B-V) \equiv (A_B^{max} - A_V^{max})$, where $A_B^{max} = B_d^{max} - B^{max}$ and $A_V^{max} = V_d^{max} - V^{max}$ with B^{max} and V^{max} being the B and V band maximum magnitudes with no dust extinction, respectively, and B_d^{max} and V_d^{max} the B and V band maximum magnitudes with dust extinction, respectively. By comparing Fig. 2(a) and Fig. 2(c), it is remarkable that the inclusion of dust scattering reduces significantly the values of R_λ around optical maximum in the optical wavelength range.

The B and V band light curves and the color curve $B-V$ are shown in Fig. 3. The presence of dust alters the light curves shapes, results in light curves with steeper rises and flatter decreases. This affects the measurements of light curve parameters. It is worth pointing out that the peculiar SN 2000cx showed qualitatively a fast rise and a slow decline in B and V bands (Li et al. 2001; Candia et al. 2003) which is consistent with the above behavior. We defer quantitative analyses of individual SN to future studies, but note here that the presence of CS dust can be tested on individual basis of well observed SNe.

Fig. 4 shows that scattering has smaller effect around optical maximum for dust wind located at larger distances. More distant dust clouds, however, do affect later time light curves.
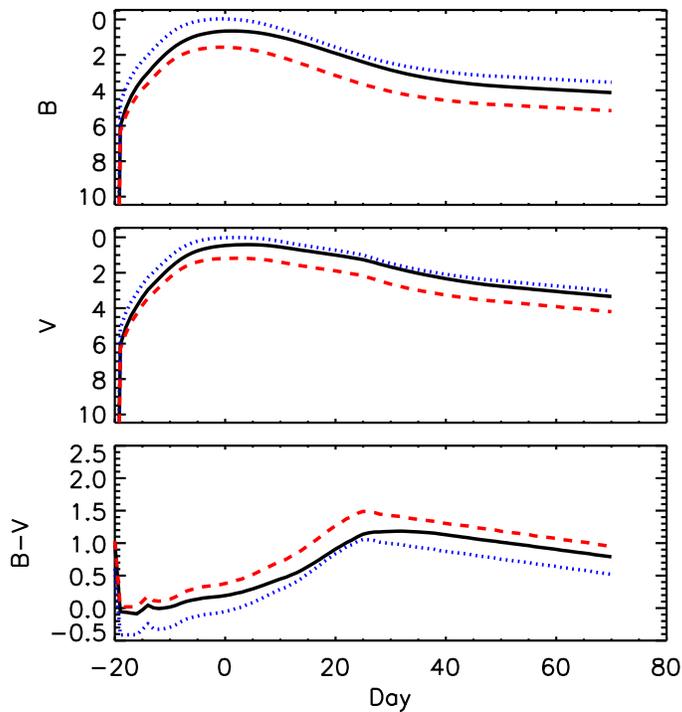
Fig. 3.— The B (upper panel), V (middle panel) light curves and $B - V$ color curves (lower panel) of Type Ia supernova. The dotted lines show the input data. The dashed lines show the light curve expected for Case A where scattered photons are all unobserved. The solid lines show the results when scattering and absorption are treated properly by inclusion of the time delayed scattered photons. The geometry and opacity of the dust are the same as in Fig. 2.
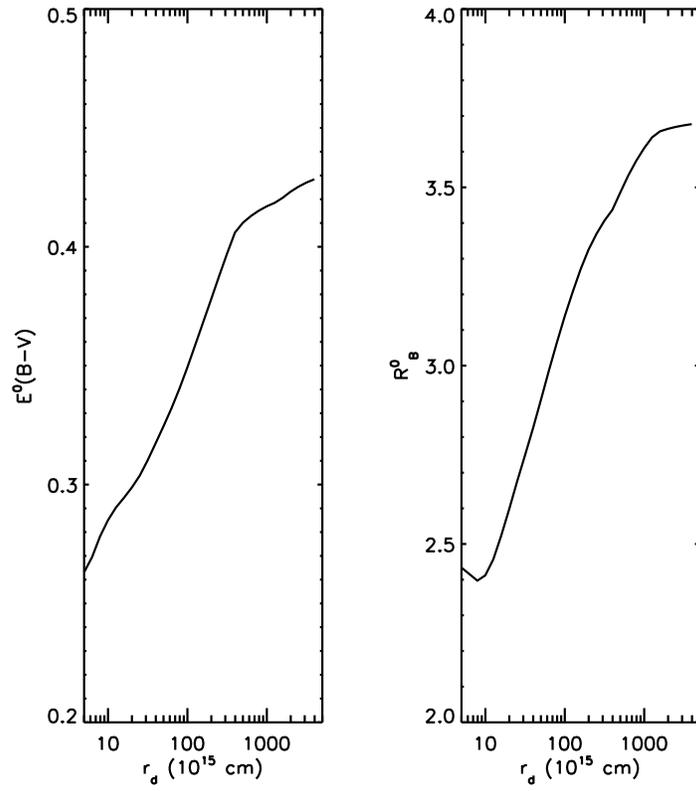
Fig. 4.— The effect of dust scattering as a function of the inner boundary of the dust clouds. (a), left, shows the color-excess, and (b), right, shows R^0_λ as defined in §3.2.

4.   Discussions and conclusions

This study shows that the low values of R_B observed SNe Ia may be an indication of the presence of dust in the immediate neighborhood of SNe Ia. Dust of extinction properties similar to that of the LMC can explain the observed unusually low R_B values for SNe Ia, provided that they are distributed in the circumstellar environment of the SNe. Although not required by the current analyses, it should be reminded that CS dust may have substantially different extinction properties compared to interstellar dust. However, the presence of even a small amount of CS dust leaves clear imprints on the light curves of SNe Ia and can be tested by careful observations of SN Ia light curves.

High resolution spectroscopy has set some upper limits on the amount of CSM around SN 1994D (Cumming et al. 1996) and SN 2001el (Mattila et al. 2005). The strongest constraint is a mass loss rate of around $10^{-5} M \odot$ /year for a wind velocity of 10 km/s derived for SN 2001el 9 days before optical maximum. Note that at this early date, only CSM at distances lower than $3\ 10^{15}$ cm are interacting with the SN ejecta, and the observations are not sensitive to CSM at even larger distances. These observations are thus insensitive to nebular structures with a central bubble such as often encountered in PNe.

As noticed in Wang et al. (2004) and Deng et al. (2004), several other SNe previously identified as SN IIn are in fact strikingly similar to SN 2002ic at late stages. These include SN 1988Z (Turatto et al. 1993), SN 1997cy (Turatto et al. 2000), and SN 1999E (Rigon et al. 2003). Model spectra of these objects seem to rule out significant amount of oxygen in the ejecta (Chugai & Danziger 1994; Turatto et al. 2000; Chugai et al. 2004). Chugai & Danziger (1994) suggested that the mass of SN 1988Z ejecta is unexpectedly low with M < 1M⊙. The low mass ejecta and the absence of oxygen are consistent with SN Ia explosions. If these are all SN 2002ic-like SNe, and taking the number of SN Ia discoveries at their face value, it would imply that about 1% of all SNe Ia are associated with dense nebula similar to SN 2002ic. There may be a substantial fraction of SNe Ia with significant amount of undetected CS materials. This is corroborated by recent SN Ia rate studies which indicate that about 50% of the observed SNe Ia are produced by progenitors probably more massive than 5.5 M⊙, in a time scale of the order of 10^8 years after the progenitor birth (Mannucci et al. 2005). Livio & Riess (2003) argue merging of two white dwarfs might be responsible for events such as SN 2002ic, whereas Chugai et al. (2004) argue for the Type 1.5 SN scenario proposed by Iben & Renzini (1983) in which the explosion is due to a star at the end of the post-AGB phase (Iben & Renzini 1983). These models would produce SNe Ia with dense CSM envelope. It is not clear in what parameter range can these different models produce successful supernovae. Studies of CS dust around SNe Ia can be performed and be used as probes of the progenitor systems and explosion mechanisms.

Another source of dust in the immediate neighborhood of SNe Ia may be the ejecta themselves. The thermonuclear reaction lasts only for a second after the SN explosion. During which the ejecta reach a temperature of 10^9 K and an expansion velocity of 25,000 - 30,000 km/sec. The temperature of the ejecta decreases rapidly due to adiabatic cooling and reaches a temperature of about 10^3 K in only about a few minutes. This rapid cooling allows for the condensation of dust in the ejecta. Most of these dust, however, are likely to be quickly destroyed by radioactive heating as the ejecta are reheated to temperatures around 10,000 K. But the dust formation may be patchy and some dense clumps may survive the radiation field of the supernova, especially at the highest velocity layers that are shielded from the bombardment of the radioactive decays deeper.

In summary, the signatures of CS dust can be recognized by analyzing light curves of SNe Ia. Observations of wide wavelength coverage from UV to the near-IR offer the best hope for discriminating interstellar dust from CS dust. Spectropolarimetry is another method for studying interstellar dust, as shown in Wang & Wheeler (1996) for SN 1987A.

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