The Astrophysical Journal, 635:L33–L36, 2005 December 10

DUST AROUND TYPE Ia SUPERNOVAE

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Received 2005 October 7; accepted 2005 October 21; published 2005 November 29

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 multiepoch spectropolarimetry of Type Ia supernovae.

Subject headings: distance scale — dust, extinction — supernovae: general

Online material: color figures

1. INTRODUCTION

Dust extinction of Type Ia supernovae (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 cannot 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 6 $M_\odot/(n/10^8\ \mathrm{cm}^3)$ (Hamuy et al. 2003; Wang et al. 2004; Wood-Vasey et al. 2004; Deng et al. 2004; Kotak et al. 2004). Wang et al. (2004) deduced from spectropolarimetry observations that the hydrogen-rich materials are distributed in an asymmetric, perhaps disklike geometry. Such a massive envelope, if it exists in the Galaxy, must be easily observable. It can in fact be identified with well-studied post–asymptotic giant branch (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 an environment in which the surrounding nebulosity is more diluted. PPNe ultimately evolve to planetary nebulae (PNe), which then disperse into the interstellar medium 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 10–100 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 $(\tau_B/1)(10{,}000\ \mathrm{yr}/t)^2$, where t is the dynamical age of PNe, which is typically around 10,000 years. It thus takes about 10^5 yr for the dust to be diluted to $\tau < 0.01$—a level that is still sensitive to modern SN Ia observations. Dust in PNe is distributed in patchy opaque clumps such as observed in the Helix Nebula (O'Dell et al. 2004). These dusty clumps may survive even longer timescales. 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 (hereafter case A), 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 directs photons off the lines of sight. If, on the other extreme (hereafter case B), we assume that all of the scattered photons eventually escape from the system, the corresponding attenuation will be $e^{-\tau(1-\omega)}$, 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 $A^0_\lambda = A_\lambda[1-\omega(\lambda)]$. A complete description of the amount of extinction

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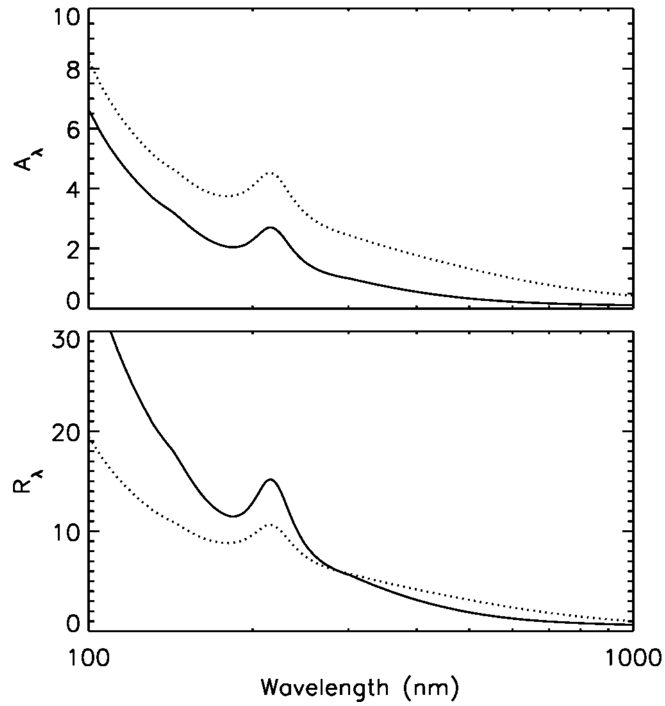

FIG. 1.—Extinction properties of the dust model of Weingartner & Draine (2001) for the LMC average. The dotted lines show the total extinction (*top panel*) and the ratio of total extinction to $E(B-V)$ (*bottom panel*) if the scattered photons are all unobservable (case A; see text). The solid lines show the corresponding quantities assuming a single photon-dust interaction, and all scattered photons escape from the dust shell and are observable (case B; see text). The extinction curves for case A are dramatically different from those for case B.

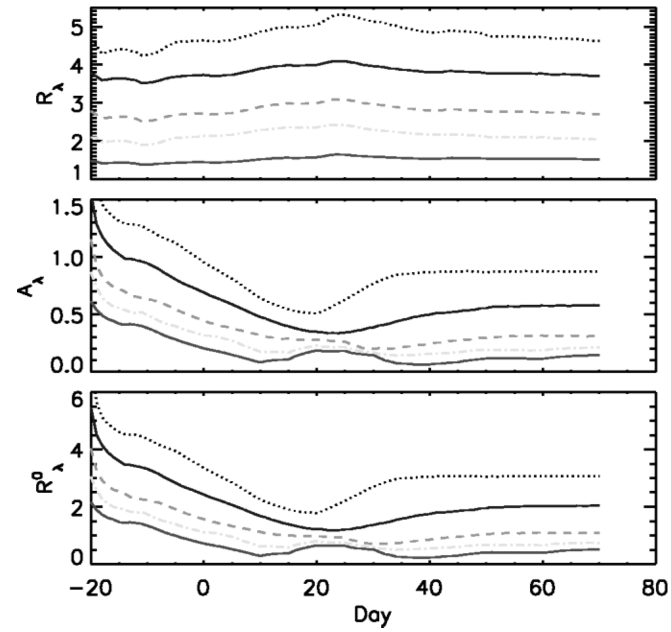

FIG. 2.—Time dependence of extinction properties in *U* (*dotted line*), *B* (*solid line*), *V* (*dashed line*), *R* (*dot-dashed line*), and *I* (*triple–dot-dashed line*) bands for Type Ia supernovae. The top panel shows the effect on R_λ due to spectral time evolution. The middle panel and bottom panel show the A_λ and R^0_λ as defined in § 3.3, respectively. The curves in the middle and bottom panels 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 the *B* band. [*See the electronic edition of the Journal for a color version of this figure.*]

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 Figure 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 wavelengths longer than 300 nm, whereas it is significantly increased at wavelengths shorter than 300 nm.

Case A is applicable for extinction by interstellar dust. Case B is applicable for extinction by dust envelopes that cannot be spatially resolved from the target, such as the compact CS dust of stars or the circumnuclear dust in the host galaxies of active galactic nuclei or quasi-stellar objects.

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 Figure 2 (*top panel*) R_λ at different epochs for a typical SN Ia. R_λ shows ∼20% variations. This effect should be important when using SNe Ia for cosmology but cannot explain the observed low R_B for SNe Ia.

3.3. *The Time Dependency of Dust Scattering*

Light reflected off dust particles travels a 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 echoes are observed in several nearby 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), who showed 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 the middle and bottom panels of Figure 2, 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 the *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 $3.3 \times 10^{-5}\ M_\odot\ \mathrm{yr}^{-1}$.

As shown in the middle panel of Figure 2, 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 in the contributions of scattered photons to the total flux. The effective extinction is in general smaller than when dust scattering is ignored. The bottom panel of Figure 2 shows the effective ratio of extinction to color excess. To be consistent with SN Ia observations, this is defined here as $R^0_\lambda = A_\lambda/E^0(B-V)$, with $E^0(B-V) \equiv (A^{\max}_B - A^{\max}_V)$, where $A^{\max}_B = B^{\max}_d - B^{\max}$ and $A^{\max}_V = V^{\max}_d - V^{\max}$, with $B^{\max}$ and $V^{\max}$ being the *B*- and *V*-band maximum magnitudes with no dust extinction, respectively, and $B^{\max}_d$ and $V^{\max}_d$ being the *B*- and *V*-band maximum

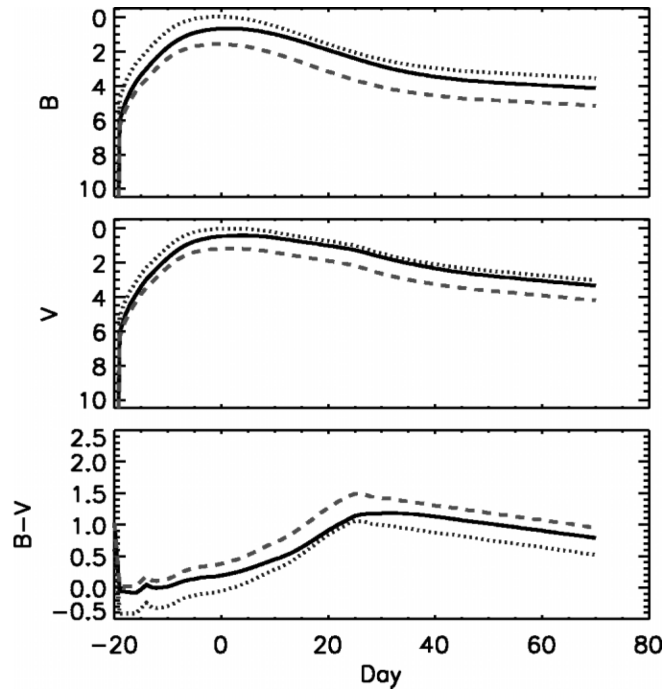

FIG. 3.—*B* (*top panel*) and *V* (*middle panel*) light curves and $B - V$ color curves (*bottom panel*) of Type Ia supernovae. The dotted lines show the input data. The dashed lines show the light curve expected for case A, where the scattered photons are all unobserved. The solid lines show the results when scattering and absorption are treated properly by the inclusion of the time-delayed scattered photons. The geometry and opacity of the dust are the same as in Fig. 2. [*See the electronic edition of the Journal for a color version of this figure.*]

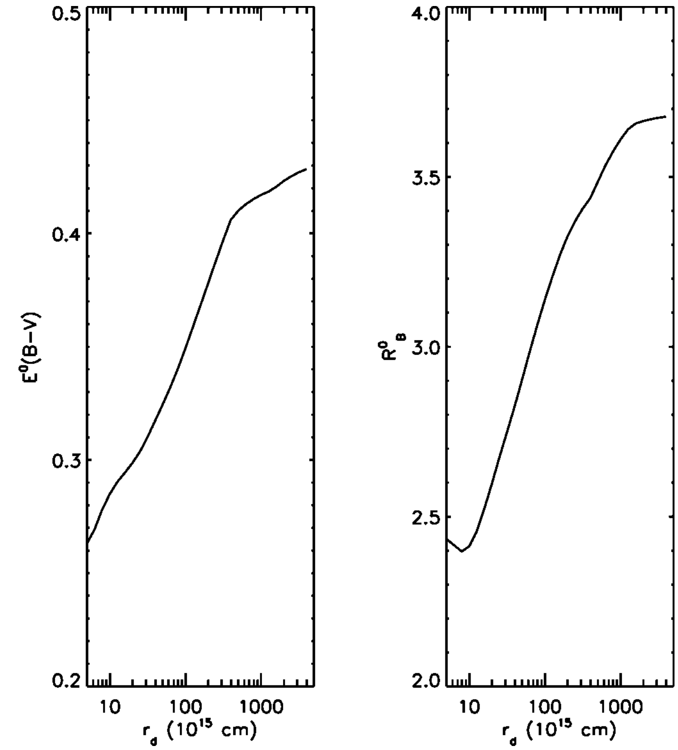

FIG. 4.—Effect of dust scattering as a function of the inner boundary of the dust clouds. The left panel shows the color excess, and the right panel shows R_λ^0 as defined in § 3.2.

light magnitudes with dust extinction, respectively. By comparing the top panel with the bottom panel of Figure 2, 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 Figure 3. The presence of dust alters the light curve shapes, resulting 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 the *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 an individual basis on well-observed SNe.

Figure 4 shows that scattering has a smaller effect around the optical maximum for dust wind located at larger distances. More distant dust clouds, however, do affect later time light curves.

4. DISCUSSIONS AND CONCLUSIONS

This study shows that the low values of R_B observed in SNe Ia may be an indication of the presence of dust in the immediate neighborhood of SNe Ia. The 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, I would like to remind the reader that CS dust may have substantially different extinction properties than 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 circumstellar matter (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 $10^{-5}\ M_\odot\ \mathrm{yr}^{-1}$ for a wind velocity of 10 km s^{-1} 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 is often encountered in PNe.

As noticed in Wang et al. (2004) and Deng et al. (2004), several other SNe previously identified as SNe 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 amounts 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 $M < 1\ M_\odot$. 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 amounts of undetected CS materials. This is corroborated by recent SN Ia rate studies indicating that about 50% of the observed SNe Ia are produced by progenitors probably more massive than 5.5 $M_\odot$, on a timescale of the order of 10^8 yr after the progenitor birth (Mannucci et al. 2005). Livio & Riess (2003) argue that the 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 envelopes. It is not clear in what parameter range these different models can produce successful supernovae. Studies of CS dust around SNe Ia can be performed and can 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 s^{-1}. The temperature of the ejecta decreases rapidly due to adiabatic cooling and reaches a temperature of about 10^3 K in only a few minutes. This rapid cooling allows for the condensation of dust in the ejecta. Most of this dust, however, is 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 better shielded from the bombardment of the radioactive decays.

In summary, the signatures of CS dust can be recognized by analyzing the light curves of SNe Ia. Observations of wide-wavelength coverage from the UV to the near-IR offer us 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.

I am grateful to G. Aldering, S. Perlmutter, M. Strovink, A. Witt, and D. York for helpful discussions.

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