CAN LIGHT ECHOES ACCOUNT FOR THE SLOW DECAY OF TYPE IIn SUPERNOVAE?

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ABSTRACT

The spectra of Type IIn supernovae indicate the presence of a preexisting slow, dense circumstellar wind (CSW). If the CSW extends sufficiently far from the progenitor star, then dust formation should occur in the wind. The light from the supernova explosion will scatter off this dust and produce a light echo. Continuum emission seen after the peak will have contributions from both this echo as well as from the shock of the ejecta colliding with the CSW, with a fundamental question of which source dominates the continuum. We calculate the brightness of the light echo as a function of time for a range of dust shell geometries and use our calculations to fit to the light curves of SN 1988Z and SN 1997ab, the two slowest declining Type IIn supernovae on record. We find that the light curves of both objects can be reproduced by the echo model. However, their rate of decay from peak, color at peak, and observed peak absolute magnitudes when considered together are inconsistent with the echo model. Furthermore, when the observed values of $M_B$ are corrected for the effects of dust scattering, the values obtained imply that these supernovae have unrealistically high luminosities. We conclude that light echoes cannot properly account for the slow decline seen in some Type IIn supernovae and that the shock interaction is likely to dominate the continuum emission.

Subject heading: supernovae: general

1. INTRODUCTION

Supernovae are designated to be of Type IIn based on their spectra (Schlegel 1990). The group is quite heterogeneous, but a typical Type IIn would have the following properties: an Hz profile composed of a narrow peak (~100 km s$^{-1}$) sitting on a broad base (~10$^4$ km s$^{-1}$), no P Cygni absorption feature, a strong blue continuum, and slow spectral evolution. There is occasionally an intermediate width component (~2000 km s$^{-1}$) to the Hz line. Absorption lines tend to be weak or absent. The narrow Hz component is seen to vary in intensity and has thus been interpreted to indicate the presence of a preexisting slow-moving stellar wind. These winds can be very dense, with $M$ as high as $10^{-2}$ $M_\odot$ yr as is the case with SN 1997ab (Salamanca et al. 1998). The overall spectral properties of these supernovae have successfully been interpreted as being due to a shock interaction between the rapidly expanding supernova ejecta and this dense ($10^6$--$10^8$ cm$^{-3}$) stellar wind (Chevalier & Fransson 1985; Chugai 1991; Terlevich 1994). Type IIn comprise about 5% of observed Type II supernovae.

A number of Type IIn supernovae show an abnormally slow decline in their light curves. SN 1997ab and SN 1988Z are the extreme examples of this, both declining by only about 5 mag in 1000 days. Simple models of the shock interaction suggest that the shock can produce sufficient optical continuum emission to account for this slow decline (Terlevich 1994; Plewa 1995). It was suggested by Chugai (1992) that light echoes might also provide a significant contribution to the late time light curves of Type IIn supernovae, i.e., the observed continuum should be a combination of shock and echo contributions. When the supernova explodes, it vaporizes any dust in the circumstellar wind (CSW) out to a radius of ~10$^{16}$ cm (Pearce & Mayes 1986). Any dust that lies outside this evaporation radius will scatter the supernova light. Scattered light travels a longer path before reaching us, so is delayed relative to any unscattered light, i.e., a light echo is produced. As little as $10^{-6}$ $M_\odot$ of dust is required to make the circumstellar shell of matter optically thick to dust scattering.

We here investigate whether light echoes could help account for the slow decline in the light curve seen in some Type IIn supernovae. We have performed a detailed calculation of the light echo produced by a range of dust shell geometries. Our assumptions and method of calculation are described in the next section. Our results are presented in § 3, and in § 4 we fit to the observed light curves of SN 1988Z and SN 1997ab. Section 5 is devoted to the discussion of our results.

2. CALCULATING THE LIGHT ECHO

The light echo in the $U$, $B$, $V$, and $R$ bands was computed by a Monte Carlo simulation. The calculation requires knowledge of the dust size distribution, the dust spatial distribution, the optical properties of the dust, and the underlying Type II supernova light curve.

The dust was assumed to be composed of a mixture of silicon and graphite grains, in the ratio 3:1 by number. Both grain types were assumed to have a grain size distribution described by the Mathis, Rumpl, & Nordsieck (MRN) grain model (e.g., Evans 1994), i.e., the number density of grains varies as $n(a) \propto a^{-3.5}$, where $a$ is the grain diameter. Our grain size ranged from $a_{\text{min}} = 0.005$ $\mu$m up to $a_{\text{max}} = 1.0$ $\mu$m.

We assumed that the dust lies in a spherical shell of inner radius $R_{\text{min}}$ and outer radius $R_{\text{max}}$ about the star. $R_{\text{min}}$ is the radius out to which the supernova evaporates all the dust in the CSW. $R_{\text{min}}$ can be estimated from first principles and for a Type II supernova has a value of a few times 10$^{16}$ cm (Pearce & Mayes 1986). We used this value as a guide, and took both $R_{\text{min}}$ and $R_{\text{max}}$ to be free parameters. We assumed that the dust density in the shell varies as $\rho(r) \propto r^{-2}$. The amount of dust in the shell is characterized by $\tau$, the $R$-band
optical depth for a purely radial photon trajectory. The total dust mass is related to $q$ by the following expression:

$$M_{\text{dust}} = \frac{8\pi}{3} (a_{\text{max}}^{0.5} - a_{\text{min}}^{0.5}) R_{\text{max}} R_{\text{min}} \left[ f_{\rho_{\text{gr}}} + (1 - f) \rho_{\text{Si}} \right]$$

$$\times \left[ \int_{a_{\text{min}}}^{a_{\text{max}}} da a^{-1.5} \sum_{i=\text{abs,scat}} \tau_{Q_i} \right]$$

$$= 7.0 \times 10^{-7} \left( \frac{R_{\text{min}}}{0.01 \text{ pc}} \right) \left( \frac{R_{\text{max}}}{1.0 \text{ pc}} \right) M_\odot,$$

where $f = 0.25$, $\rho_{\text{gr}} = 2.5 \text{ g cm}^{-3}$, and $\rho_{\text{Si}} = 2.35 \text{ g cm}^{-3}$ are the densities of graphite and silicon, respectively, and $Q_{\text{abs}}$ and $Q_{\text{scat}}$ are the absorption and scattering efficiencies.

Either the photons are absorbed by the dust or they scatter elastically. The cross sections for the dust-photon interactions are functions of both the photon wavelength and the dust grain size. We used the scattering and absorption cross sections, $\sigma_{\text{abs}}(=4\pi a^2 Q_{\text{abs}})$ and $\sigma_{\text{scat}}(=4\pi a^2 Q_{\text{scat}})$, calculated by Draine (1987). The angular distribution for the scattering is given by the Henyey-Greenstein function (Henyey & Greenstein 1941),

$$F(\theta) = \frac{1 - g^2}{(1 + g^2 - 2g \cos \theta)^{3/2}},$$

where $g$ is the degree of forward scattering and is a function of wavelength and grain size. Values for $g$ were also taken from Draine (1987).

We used the composite II-L and II-P light curves calculated by Doggett & Branch (1985) as input (Fig. 1). They provide averaged light curves for the $B$ and $V$ bands. We took the $U$ and $B$ bands to be initially identical, and likewise the $V$ and $R$. The input supernova was taken to have $B-V = 0$ at peak.

Our Monte Carlo code follows the photon trajectories in three dimensions. It keeps track of the time delay for each photon, as well as the photon weight. The weight was decreased at each interaction by the absorption probability. The photon was also split at each interaction into a part that has no further interactions and thus escapes, and a second part that is forced to interact at least once more. This substantially improves the output statistics. Our code was tested against a number of analytical test cases, and also against the calculations of Chevalier (1986), who calculated light echoes in the limit of low optical depth.

Our code produces the $R$-band light curve as well as the $V-R$, $B-V$, and $U-B$ colors as output. The output is dependent on the choice of $R_{\text{min}}$, $R_{\text{max}}$, and $q$. A total of $10^6$ input photons were used to calculate each band for each choice of the model parameters. Our output does not include any contribution from line emission.

### 3. RESULTS

Our echo model has three parameters: $R_{\text{min}}$, $R_{\text{max}}$, and $q$. Figures 2, 3, and 4 show the effect of varying each of these in turn. We see from the figures that the echo is fairly insensitive to both $R_{\text{min}}$ and $R_{\text{max}}$, as long as the shell is thicker than a few hundredths of a parsec. As the shell becomes thinner, the light curves fall off faster, and more closely trace the intrinsic light curve. We can also see that the presence of a small amount of dust has a pronounced effect on the light curve at late times. The optical depths in the $U$, $B$, $V$, and $R$ bands are always in the ratio $1.56:1.35:1.20:1.00$. The $V-R$, $B-V$, and $U-B$ colors remain nearly constant after
Fig. 2.—Effect on the light curves due to changes in $\tau$, $R_{\text{min}}$, and $R_{\text{max}}$ are held fixed at 0.1 and 1.0 pc, respectively. (a) and (b) show the $R$-band light curve for input II-L and II-P, respectively. The remaining plots are for $V-R$, $B-V$, and $U-B$ for each of the two sets of input. The curves have been shifted downward by $\Delta$ mag for clarity.
Fig. 3.—Effect of changes in $R_{\text{max}}$. The curves are for $R_{\text{min}} = 0.01, 0.5, 0.95,$ and $0.99$ pc. $\tau$ is held fixed at 1.0 and $R_{\text{max}}$ at 1.0 pc. (a) and (b) show the $R$-band light curves for input II-L and II-P, respectively. The remaining plots are for $V - R$, $B - V$, and $U - B$ for each of the two sets of input. The curves have been shifted downward by $\Delta$ mag for clarity.
FIG. 4.—Effect of changes in $R_{\text{max}}$. The curves are for $R_{\text{max}} = 0.11, 0.15, 0.5, 1.0,$ and $2.0$ pc. $r$ is held fixed at 1.0 and $R_{\text{min}}$ at 0.1 pc. (a) and (b) show the $R$-band light curves for input II-L and II-P, respectively. The remaining plots are for $V-R$, $B-V$, and $U-B$ for each of the two sets of input. The curves have been shifted downward by $\Delta$ mag for clarity.
about 200 days for all the non–thin-shell cases. For the thin shells the colors tend to redden at late times.

While there are variations amongst models, the following relations serve as useful approximations:

\[
(U - B)_{\text{peak}} \sim 0.17\tau,
\]
\[
(B - V)_{\text{peak}} \sim (V - R)_{\text{peak}} \sim 0.15\tau,
\]
\[
\Delta m_U \sim 1.4\tau,
\]
\[
\Delta m_B \sim 1.3\tau,
\]
\[
\Delta m_V \sim 1.1\tau,
\]
\[
\Delta m_R \sim 0.95\tau,
\]
\[
\beta_{100,U} \sim 4.3 - 1.5\tau,
\]
\[
\beta_{100,V} \sim 4.3 - 1.4\tau,
\]
\[
\beta_{100,V} \sim 4.0 - 1.2\tau,
\]
\[
\beta_{100,R} \sim 4.0 - 1.1\tau,
\]

where \(\Delta m\) is the number of magnitudes by which the peak of the light curve has faded due to dust scattering compared to the peak in the composite Type II light curve, and \(\beta_{100}\) is the number of magnitudes by which the light curve drops from peak over the first 100 days after peak.

4. FITS TO SN 1988Z AND SN 1997ab

SN 1988Z and SN 1997ab are the two slowest declining Type II supernovae on record. (SN 1995N has a similar decay rate, but data on this object are not yet available.) The slow decline suggests that these objects are embedded in a dense CSW. This is borne out by analysis of the spectra of these objects. Salamanca et al. (1998) calculate that the electron density in the CSW of SN 1997ab has a value close to \(10^3\) cm\(^{-3}\). Chugai (1992) found a similar result for SN 1988Z. We have used our echo model to fit to the light curves of these two supernovae.

4.1. SN 1988Z

SN 1988Z was discovered on 1988 December 12 in the galaxy MCG +03-28-022 (Cappelloro & Turatto 1988). The supernova was past peak at this time, but its high luminosity \((m_B = 16.75, M_B = -18.3 \text{ for } H_0 = 65 \text{ km s}^{-1} \text{ Mpc}^{-1})\) argues that the maximum occurred not long before discovery. The supernova faded monotonically at an unusually slow rate. Over the first 137 days it faded by only 1.5 mag in both the \(B\) and \(V\) bands, whereas the composite II-L light curve drops by some 5 mag over the same period. The color evolution of SN 1988Z is very unusual (Turatto et al. 1993). Over the first 100 days \(B - V\) decreases from 0.4 to 0.1 mag. The supernova then becomes redder, until the color reaches a constant value of about 0.65 mag after 700 days. Figure 5 shows our fit to the \(B\) and \(V\) band light curves of SN 1988Z. The \(B\)-band fit corresponds to \(\tau = 2.0 \pm 0.2\), \(R_{\text{min}} = 0.10 \pm 0.02\) pc, and \(R_{\text{max}} = 0.35 \pm 0.05\) pc. This corresponds to a dust mass in the shell of (eq. [1]) \((4.9 \pm 1.1) \times 10^{-6} M_\odot\). The narrow component of the H\(\alpha\) line is unresolved, so if we adopt a value of 100 km s\(^{-1}\) for the wind velocity, and assume a constant mass-loss rate, we infer that the progenitor star emitted material for about 3400 yr before going supernova at a rate of \((1.3 \pm 0.3) \times 10^{-6} (f_{\text{dust}}/10^{-3})^{-1} M_\odot\) yr\(^{-1}\), where \(f_{\text{dust}}\) is the fraction of the wind mass that has formed into dust. The fit to the \(B\) band determines the fit to the \(V\) band, i.e., the \(V\) band is not fit separately. In both cases, the fit is reasonably good up to about 800 days, after which the observed light curves are seen to flatten significantly with respect to the model predictions.

4.2. SN 1997ab

SN 1997ab was discovered on 1996 April 11 in the galaxy HS 0948+2018 (Hagen & Reimers 1997). It had a \(B\) magnitude of 14.7, which corresponds to an absolute magnitude \(M_B = -19.1 \text{ for } H_0 = 65 \text{ km s}^{-1} \text{ Mpc}^{-1}\). The date of peak is uncertain, but the high luminosity at discovery argues that the peak had occurred recently. The light curve of this object is not well sampled unfortunately, there being only three other \(B\)-band observations and two \(V\)-band observations since discovery (Hagen, Engels, & Reimers 1997; Schaefer & Roscherr 1998, 1999).

Our model fits the \(B\)-band light curve (Fig. 6) for \(\tau = 3.0 \pm 0.3\), \(R_{\text{min}} = 0.10 \pm 0.02\) pc, and \(R_{\text{max}} = 0.30 \pm 0.05\) pc. This implies a dust mass in the shell of...
(6.3 ± 1.4) × 10⁻⁶ M⊙. The wind velocity is measured to be 90 km s⁻¹, and so we infer that the progenitor emitted material for some 3000 yr before going supernova at an average rate of (2.9 ± 0.7) × 10⁻⁶ (f_dust/10⁻⁵)⁻¹ M⊙ yr⁻¹. Salamanca et al. (1998) find a mass-loss rate of approximately 10⁻² M⊙ yr⁻¹ from the analysis of the spectrum of this object. They find that the emitted material lies in a shell that extends no more than 0.05 pc from the progenitor. This implies that the progenitor had a brief episode of strong mass loss shortly before going supernova. The material emitted during this episode lies too close to the star to allow any dust formed to survive the supernova explosion. The dust that is responsible for the echo must have been emitted during an earlier, more sustained period of lower mass loss.

5. ECHO MODEL VERSUS SHOCK MODEL

If the progenitors of Type II supernovae emit material for more than a few hundred years prior to going supernova, then they should be surrounded by a dusty CSW. All the dust that lies beyond the evaporation radius of the supernova will scatter the supernova light and produce a light echo. There is likely to be an echo component in the light curves of many Type II supernovae, the only question is how significant a component it is.

We have seen in the previous section that the echo model can provide reasonably good fits to the light curves of SN 1988Z and SN 1997ab. Chugai (1992), however, produced a similar quality fit to the light curve of SN 1988Z with a simple model of the shock continuum emission. Fits to the light curves alone are thus not sufficient to discriminate between the models.

In Figure 7 we have plotted (B − V)peak versus ρ₁₀₀,B. The region between the two solid lines is the region of parameter space allowed by the echo model. As the amount of circumstellar dust increases, we expect the supernova light to suffer more scatterings, producing an echo that becomes progressively redder and longer lived. In shock models the optical light is primarily produced by the reprocessing of X-rays. The color of the optical light produced in this way is not very sensitive to the amount of circumstellar material present, so on the plot of (B − V)peak versus ρ₁₀₀,B, we do not expect to see a correlation. Both SN 1988Z and SN 1997ab lie within the region allowed by the echo model. The other Type IIn supernovae plotted on the figure, however, do not. Their distribution shows no definite correlation, and is thus consistent with the shock model prediction.

The Type IIn supernovae plotted represent the complete sample for which (B − V)peak, ρ₁₀₀,B, and ΔMpeak are available in the literature (Patat et al. 1994). The data for SN 1998S was taken from the CfA Supernova Group website.¹

In Figure 8 we have plotted the observed ΔMpeak versus ρ₁₀₀,B. In the echo model, for a given underlying supernova luminosity, as the dust mass increases, the decay rate decreases and the observed ΔMpeak increases, i.e., the supernova appears fainter as more of the emission at peak is scattered by the dust. The opposite trend is expected for shock models, i.e., we expect the peak luminosity to increase as the amount of circumstellar material increases. In an ΔMpeak versus ρ₁₀₀,B plot, shock models thus predict a downward-sloping line. The observed Type IIn points are consistent with the shock prediction, and inconsistent with the prediction of the echo model. In particular, the points for both SN 1997ab and SN 1988Z lie outside the region allowed by the echo model. In Figure 9 we have plotted the observed ΔMpeak versus (B − V)peak. The echo model predicts that the emission should redden as the amount of dust, and thus ΔMpeak increases. The observed data points are inconsistent with this prediction.

Another argument against the echo model is the implied values for ΔMpeak for the underlying supernovae. SN 1988Z

¹ http://cfa-www.harvard.edu/cfa/or/Research/supernova.
had an observed $M_{B,\text{peak}}$ of $-18.3$ and SN 1997ab, $-19.1$. If we use the values of $\tau$, $R_{\text{min}}$, and $R_{\text{max}}$ obtained from the fits to the light curves to find $\Delta m_B$, we find that the underlying supernovae must have had $M_{B,\text{peak}}$ of $-20.9$ in the case of SN 1988Z, and $-22.8$ for SN 1997ab. This would make these supernovae by far the brightest Type II supernovae yet observed. Our model has assumed that the dust distribution and supernova explosion have spherical symmetry. There is, however, growing evidence that the continuum emission from Type II supernovae is polarized (Leonard et al. 1999; Wang et al. 1996). This implies that both the explosion and the dust distribution may be aspherical. If this is the case, then it could reduce the implied intrinsic peak luminosities for SN 1988Z and SN 1997ab. This might weaken the argument against SN 1988Z, but not substantially affect the argument against SN 1997ab.

We conclude that light echoes cannot properly account for the slow decline seen in some Type IIn supernovae. The predictions of shock models are consistent with the data, and shocks are likely to dominate the continuum emission. The absence of a strong echo component in the light curves of Type IIn supernovae argues that the progenitors of these supernovae undergo the bulk of their mass loss just prior to going supernova, and thus very little dust survives the explosion.

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