LATE LIGHT CURVES OF TYPE Ia SUPERNOVAE

P. A. Milne\textsuperscript{1}
Naval Research Laboratory, Code 7650, Washington, DC 20375

AND

L.-S. The AND M. D. Leising
Department of Physics and Astronomy, Clemson University, Clemson, SC, 29634-0978

Received 2001 March 19; accepted 2001 June 6

ABSTRACT

We extend earlier efforts to determine whether the late (t ≥ 60 days) light curves of Type Ia SNe are better explained by the escape of positrons from the ejecta or by the complete deposition of positron kinetic energy in a trapping magnetic field. We refine our selection of Ia SNe, using those that have extensive $BVRI$ photometry 35 days or more after maximum light. Assuming that all SNe within a given $\Delta m_{15}(B)$ range form a distinct subclass, we fit a combined light curve for all class members with a variety of models. We improve our previous calculations of energy deposition rates by including the transport of the Comptonized electrons. Their nonlocal and time-dependent energy deposition produces a correction of as much as 0.10 mag for Chandrasekhar-mass models and 0.18 mag for sub-Chandrasekhar-mass models.

We produce bolometric corrections, derived from measured spectra, to $B$, $V$, $R$, and $I$ light curves after day 50. Comparisons of the resulting bolometric light curves with simulated energy deposition rates demonstrate that the energy deposition from the photons and positrons created in $^{56}\text{Co} \rightarrow ^{56}\text{Fe}$ decays are consistent with the observations if positron escape is assumed. This implies that there is no evidence of additional sources of energy deposition or of a shift of emission into unobserved wavelength ranges between days 60 and 900. The $V$ band is shown to be an accurate indicator of total emission in the 3500–9700 Å range, with a constant fraction ($\sim 25\%$) appearing in the $V$ band after day 50. This suggests that the $V$ band scales with the bolometric luminosity and that the deposited energy is instantaneously recycled into optical emission during this epoch. We see significant evolution of the colors of SNe Ia between days 50 and 170. We suggest that this may be due to the transition from spectra dominated by emission lines from the radioactive nucleus, $^{56}\text{Co}$, to those from the stable daughter nucleus, $^{56}\text{Fe}$.

Subject headings: gamma rays: observations — gamma rays: theory — supernovae: general

1. INTRODUCTION

Type Ia supernovae (SNe) are an integral part of many current astrophysical investigations. Their luminosities briefly rival those of entire galaxies, making them useful as distance indicators to high rival those of entire galaxies, making them useful as current astrophysical investigations. Their luminosities diffuse gamma-ray background in the 400–2000 keV energy range (Watanabe et al. 1999). The escape of positrons from their ejecta may be large enough to explain a majority of the range (Watanabe et al. 1999). The escape of positrons from the ejecta lowers the column density to the surface, decreasing both the time for optical photons to diffuse outward and the efficiency of trapping of gamma rays and energetic positrons and electrons. The SN thus makes the transition from an epoch during which the energy deposition is essentially complete and instantaneous and the emission depends upon the diffusion of optical photons (a “diffusion-dominated” epoch) to an epoch during which the diffusion timescale is

\footnote{Although neutrinos are also created in these decays, the lower neutrino opacity makes neutrinos an insignificant contributor to the energy deposition rate during the epoch of interest in this work. See Nadyozhin (1994) for major features of this decay chain.}

\textsuperscript{1}NAS/NRC Resident Research Associate.
negligibly short and the emerging emission depends upon the transport of the decay products (a “deposition-dominated” epoch).

Observations of SNe during these two epochs probe different characteristics of the SN explosion. As will be described in § 2, observations of SNe Ia during both epochs have led to considerable advances in the understanding of the SN event. This work concentrates upon late emission. It follows a previous work (MTL) which also investigated late emission, fitting model-generated energy deposition rates to photometry of 10 SNe Ia. That work treated the time period from day 50 to day 200 in an approximate fashion, concentrating upon the emission between days 200 and 1000, and it will be referenced for discussions relating to gamma-ray, X-ray, and positron transport and the yield of escaping positrons. This work performs similar comparisons, but concentrates more on the day 50–day 200 period, which spans the transition from diffusion-dominated to deposition-dominated emission. In addition, this paper treats the information available from the R- and I-band observations of SNe Ia, as well as from late spectra. We compare model-generated energy deposition rates with B-, V-, R-, and I-band photometry for a large collection of well-observed SNe Ia, before and after creating bolometric corrections from a collection of late SN Ia spectra. Through these comparisons, we address four specific questions. (1) Is there any order to the late light curves of SNe Ia? (2) Is there observational support for the suggestion that positrons escape the SN ejecta? (3) Do the late light curves afford any insight into the correct explosion scenario(s)? (4) Are the late light curves of SNe Ia suitably explained by the products of the $^{56}\text{Ni} \rightarrow ^{56}\text{Co} \rightarrow ^{56}\text{Fe}$ decay without the inclusion of additional sources of energy deposition?

2. PHYSICS OF SN Ia EMISSION

2.1. Emission during the First 50 Days

SN light curves peak in brightness and fade on timescales related to the lifetimes of $^{56}\text{Ni}$ ($\tau = 8.8$ days) and $^{56}\text{Co}$ ($\tau = 111$ days). By day 100 after the explosion, SN Ia emission has faded to less than 4% of its maximum luminosity. Largely because of the dimming of the emission, SNe Ia are better studied during the first 50 days than during later epochs. As a result, most investigations address issues relating to the diffusion-dominated epoch. Although SNe Ia were once thought to be a homogeneous class, more and better observations have revealed that intrinsic differences exist among them (Phillips et al. 1987; Filippenko et al. 1992a, 1992b; Suntzeff 1996). These differences are evident in the time evolution of the spectra, the shape of the light curves, and the absolute magnitude of the emission at peak luminosity. Inhomogeneity at the level observed has necessitated the enlargement of the paradigm from a single, standard model to families of models.

The level of understanding of this inhomogeneity has progressed on many fronts over the last decade. Observationally, “twins” have been found for both anomalously bright and anomalously faint SNe Ia, solidifying the existence of a large range (and perhaps a continuum) of phenomena. The very existence of inhomogeneity has altered the investigations of explosion scenarios. Four explosion scenarios dominate the present paradigm. The first consists of a carbon-oxygen white dwarf near the Chandrasekhar mass accreting hydrogen or helium from a binary companion until it reaches a mass at which the core carbon ignites. If the resulting burning front accelerates to become a detonation in the outer layers of the WD, a “delayed detonation” results. If the burning front remains subsonic, the result is a “deflagration.” These Chandrasekhar-mass (CM) scenarios account for inhomogeneity by variations in the propagation of the burning front due to density and/or compositional differences in the progenitor carbon-oxygen WD. The second scenario consists of a lower mass carbon-oxygen WD accreting a helium shell, which becomes thick enough to produce a helium shell detonation. This, in turn, triggers central carbon ignition. In this sub-Chandrasekhar (SC)–mass scenario, inhomogeneity is due to the varying nucleosynthesis that results when the progenitor mass varies from 0.65 to 1.1 $M_\odot$. The third scenario merges two carbon-oxygen white dwarfs, with the more massive white dwarf accreting the companion. With the CM scenario, central carbon ignition results. In this case, the accreted envelope is carbon. The masses of these explosions have been suggested to range from 1.2 to 1.8 $M_\odot$, with a roughly constant nickel yield. This scenario is also referred to as a “double degenerate” explosion. The fourth scenario is not a thermonuclear explosion at all, but an accretion-induced collapse (AIC) of a white dwarf (either CO or ONeMg). It has been argued that, in some cases, electron capture within an accreting white dwarf may lead to a collapse rather than central carbon ignition (as with Types II, Ib, and Ic SNe). These events eject less total mass and less nickel than those following the other scenarios, and they have been suggested to explain subluminous SNe Ia.

Families of SN models have been developed within these scenarios (including variations of the scenarios, such as pulsed delayed detonations). The reader is directed to various review papers, which assess the individual explosion scenarios (see Leibundgut 2000; Livio 2000; Nomoto et al. 2000). Many authors have demonstrated that compositional and kinematic differences within families of these SN models can roughly simulate spectral variations in observed SNe. These differences are seen and simulated near peak luminosity (Mazzali, Lucy, & Butler 1992; Mazzali, Danziger, & Turatto 1995; Mazzali et al. 1997; Höflich et al. 1996; Jeffery et al. 1992; Baron et al. 1996) and during the later, nebular epoch (Ruiz-Lapuente & Lucy 1992; Ruiz-Lapuente & Filippenko 1996; Liu, Jeffery, & Schultz 1997a, 1997b, 1998; Bowers et al. 1997).

The investigation of inhomogeneity affects the use of SNe Ia as distance indicators at the level currently employed. There is an apparent absolute luminosity-peak width relationship inferred from distance estimates to the host galaxies of nearby SNe Ia, quantified variously as $\Delta m_{15}(B)$ (Phillips 1993), MLCS (Riess, Press, & Kirshner 1996), and stretch ($\xi$; Perlmutter et al. 1997). The ability to theoretically explain the luminosity-peak width relationship is critical for relating well-observed, nearby SNe to SNe at the cosmological distances at which SNe Ia are used as distance indicators. This task is difficult because calculating the transport of

---

3 In this work, all SNe Ia will be assumed to rise to peak luminosity in 18 days.

4 Li et al. (2000) concluded that only 64% of all SNe Ia are normally luminous, with ~16% subluminous and ~20% superluminous.
optical photons through SN ejecta is a very complicated procedure. The ejecta is constantly evolving in both density and temperature. A photon crossing this nonequilibirated ejecta is redshifted (or blueshifted) relative to local matter, wreaking havoc with the line-dominated opacity. Further complicating matters are the uncertainties of the cross sections of many relevant interactions. Despite these difficulties, detailed studies have been performed. Höflich (1995) fitted the $B$, $V$, $R$, and $I$-band observations of the well-observed SN 1994D with a variety of CM models, demonstrating a high level of discrimination between models. Höflich & Khokhlov (1996) then generated $B$--$M$-band light curves for CM and SC models and fitted $B$, $V$, $R$, and $I$-band observations of 26 SNe Ia. One conclusion from that study is that SC models seem too blue at peak to explain observations of subluminous SNe Ia. The same conclusion was reached by Nugent et al. (1997). Pinto & Eastman (2000a, 2000b, 2001) investigated the influence of progenitor mass, nickel mass, nickel distribution, explosion energy, and opacity upon the bolometric light curves. They then concentrated upon the ability of CM models to reproduce the $B$, $V$, and $R$ luminosity-peak width relation in the range $0.85 \text{ mag} \leq \Delta m_{15}(B) \leq 1.75 \text{ mag}$. A significant achievement of those efforts is the agreement between their calculated $18$--$20$ day rise times of the $B$ and $V$ peak luminosity and the observed rise times of SNe Ia (Riess et al. 1999a, 1999b; Aldering, Knop, & Nugent 2000). Similarly, Mazzali et al. (2001) reproduced the luminosity-peak width relation between $1.1 \text{ mag} \leq \Delta m_{15}(B) \leq 1.5 \text{ mag}$ by varying the mass of $^{56}\text{Ni}$ in CM models.

Collectively, these investigations have reached the loose consensus that the CM explosion scenario is the favored scenario to account for the range of optical observations. Whether any subset of SN Ia events occur as SC, merger, or AIC explosions remains unclear. In this work, we simulate light curves for models representative of all four scenarios and demonstrate general results of late light-curve studies.

### 2.2. Emission after 50 Days

Neither Höflich & Khokhlov (1996) nor Pinto & Eastman carried their photometric simulations beyond day 120, both groups suggesting that their simulations become inadequate at late epochs. As described in MTL, during the time interval of interest in this work, the energy deposition is dominated by interactions involving the decay products of the $^{56}\text{Co} \rightarrow ^{56}\text{Fe}$ decay: gamma-ray photons and positrons. The photons possess $\sim 30$ times more energy per decay than the positrons but are more penetrating. This leads to an initial dominance of the energy deposition by the photons, with a transition at later times to positron dominance. The photon transport was performed with a Monte Carlo algorithm, adopting the prescription of Podznyakov, Sobol, & Sunyaev (1983). A detailed description of the Monte Carlo algorithm is given in The, Burrows, & Bussard (1990), with its application to SNe Ia light curves in Burrows & The (1990). The dominant interaction is Compton scattering, which produces energetic electrons. These secondary electrons have a mean energy of typically $300$ keV at day 100. MTL assigned these electrons zero lifetimes, depositing the energy in situ. This work improves on that by including the transport of the secondary electrons with the same algorithm employed for the positron transport, but using Möller scattering rather than Bhabha scattering. The effect of the secondary electron transport is small but non-negligible: in the CM models with radial positron escape and low ionization, the light curves are fainter by $\leq 0.10$ mag; for low-mass SC models, the effect reaches $0.18$ mag.

Positron transport depends upon the nature of the magnetic field. Three scenarios have been suggested to model the magnetic field (Ruiz-Lapuente & Spruit 1998, hereafter RLS). The first suggests that the field is too weak to confine positrons and that positrons follow straight-line trajectories, with a fraction escaping the ejecta (Colgate, Peetschek, & Krieke 1980). The second suggests a stronger field that confines positrons, but with the field lines radially combed by the homologous expansion. The positrons spiral along these radial field lines with their pitch angles decreasing because of the field gradient (beaming), with a fraction escaping the ejecta (Chan & Linfenzelter 1993). The third scenario suggests a strong field that is turbulently disordered such that positrons mirror frequently with no net transport (Axelrod 1980). Positrons may survive nonthermally at late times, but none escape. Colgate et al. (1980) argued that the first two situations are equivalent. Simulations by MTL found this to be approximately true for most SN models. The first two scenarios will be referred to here as the “radial” scenario, and the third will be referred to as the “trapping” scenario. The differing positron escape leads to differences in model energy deposition rates, which makes late observations of SNe Ia a probe of the photon and positron transport.

The positron and secondary electron transport was performed with a Monte Carlo algorithm, as explained in MTL. The dominant energy-loss mechanisms are ionization and excitation of bound electrons for low levels of ionization and plasma excitation for higher ionization. The model-generated energy deposition rate for the SC model HED8 is shown in Figure 1. The dashed line (D) assumes instantaneous deposition of all decay energy, an assumption that is invalid because of gamma-ray photon escape by day 30. The dotted line (G) uses the results of the gamma-ray/secondary electron deposition only and assumes no deposition of positron kinetic energy. By day 100, the deposition of positron kinetic energy is an important contributor to the total energy deposition rate, but the positron lifetimes are short enough that all positron curves approximate instantaneous, in situ deposition of positron energy (In). At later times, densities in the ejecta are low enough to allow escape in the radial scenario (dark shading, $R$) and nonthermal survival in the trapping scenario (light shading, $T$). Both scenarios were calculated for a range of ionizations, from $1\%$ of all nuclei being singly ionized to all nuclei being triply ionized. Positron escape removes energy from the ejecta, leading to fainter light curves than in situ deposition. Lower ionization permits more positron escape and thus is the fainter edge of the radial curve. A trapping field permits large nonthermal lifetimes but no escape. This leads to storage of energy and a late light curve that is brighter than in situ deposition. The energy storage is at the expense of a small fraction of the deposition during the day 100--day 200.
epoch. This leads to the trapping light curves being briefly slightly fainter than the in situ deposition ($\Delta m < 0.01$ mag) and then making the transition to being much brighter than the in situ deposition. For this scenario, low ionization leads to longer lifetimes for trapped positrons. This results in greater energy storage and makes the lower ionization extreme the brighter edge of the trapping curve at late times.7

2.3. Model/Observation Comparisons

The ideal model/observation comparison would entail an explicit non-LTE (NLTE) determination of photon and positron energy deposition rates and from these rates the generation of optical/IR spectra. These spectra would then be compared with a sequence of observed SN Ia spectra, comparing the evolution of the total flux from early to very late epochs. This ideal situation is far from being realized, both computationally and observationally. Falling short of that solution, an alternative approach has been employed in numerous works: fitting energy deposition rates to multi-band photometry or estimates of the UV/optical/IR bolometric luminosity. Two issues must be addressed for these comparisons to be meaningful, photon diffusion delay and color evolution. Photon diffusion delay refers to the time delay between the energy deposition (from the scattering of gamma- and X-ray photons and slowing of positrons) and the production of the optical light that can be seen by an external observer that is due to the diffusion of optical photons out of the ejecta. This diffusion delay determines the shape of the SN light-curve peak at early times, but decreases to negligible values at late times. Thus, at late epochs, energy deposition is instantaneously recycled into optical emission. In previous studies of late light curves of SNe Ia, two approaches have been used to account for photon diffusion delay. Studies that attempt to fit observations continuously from early to late epochs derive this time delay as a function of explosion epoch. The alternative approach is to study only the late epochs and assume instantaneous recycling. Observationally, the late epoch begins when the emitted spectrum makes the transition from continuum emission to (forbidden) nebular lines. Color evolution refers to the change in the fraction of the total optical flux that a given photometric band samples as the spectrum evolves. Again, two different approaches have been employed. The first approach creates bolometric light curves from the photometry (applying weighting factors derived from spectra) and compares these light curves with model-generated energy deposition rates.8 The second approach determines the epoch after which a given photometric band scales with the total optical flux (the epoch is determined from spectra), and compares this band photometry with model-generated energy deposition rates.

Two groups who carried their investigations to late epochs have treated photon diffusion in their comparisons. Colgate et al. (1980) fitted Monte Carlo model simulations of the energy deposition rate to $B$-band data from SNe 1937C and 1972E. That work assumed a gray opacity for both photon and positron transport and a single-zone model. They concluded that positron escape was required to explain the late light curves. Cappellaro et al. (1997, hereafter CAPP) and Salvo et al. (2001) transported gamma-ray photons, positrons, and optical photons through W7-like models (scaled to various masses) with a Monte Carlo code and fitted the energy deposition rates to $V$-band data from SNe 1991T, 1994D, 1992A, 1993L, 1996X, and 1991bg.9 Those works assumed a gray opacity for photons and varied the positron opacity to fit the late light curves. They concluded that positron escape was suggested for some, but not all, normally luminous SNe Ia. They further concluded that SC–mass models can only explain the late light curves of subluminous SNe Ia if there is no positron deposition at all ($\kappa = 0$).

RLS transported gamma-ray photons and positrons through CM and SC models without treating photon diffusion delays and fitted the energy deposition rates to bolometric light curves for the SNe 1972E, 1992A, and 1991bg.10 That work concentrated upon very late times ($t \geq 100$ days), when the photon diffusion delay timescale is assumed to be short. The authors concluded that normally luminous SNe Ia make the transition from a positron-trapping phase to a positron-escape phase after day 450 and can be fitted with CM models. They further concluded that SC models best describe the subluminous SNe Ia and feature positron escape as early as day 150. MTL transported gamma-ray photons and positrons through CM and SC models and fitted the energy deposition rates to bolometric, $V$-band, and $B$-band light curves for 10 SNe, including the SNe studied by the previously mentioned groups. That work also concentrated on very late times and did not

7 The normally luminous SC model shows a relatively large escape fraction for the radial scenario compared to normally luminous CM models. Nonetheless, the basic features shown in Figure 1 are characteristic of all the SN Ia models simulated.

8 Contardo et al. (2000) discuss the issues related to generating bolometric light curves from band photometry.

9 Both Colgate et al. (1980) and CAPP transported the positrons with routines produced for photon transport. The positrons were given a speed $c$.

10 The bolometric light curves were generated from photometry for SNe 1992A and 1991bg. For SN 1972E, the bolometric light curve was generated from a series of optical spectra.
treat photon diffusion delays. The authors concluded that both CM and SC models can explain normally luminous and superluminous SNe Ia, with positron escape suggested to be consistent with seven of the eight SNe. They further concluded that none of the models tested could explain the subluminous SN 1991bg, a result in agreement with CAPP but in disagreement with RLS.

This work does not simulate photon diffusion delays, but rather compares model-generated energy deposition rates to multiband photometry as though the delays were negligible. This approach uses the comparisons to determine the onset of instantaneous recycling. Similarly, the initial comparisons of the model-generated energy deposition rates to each of the $B_\nu$, $V_\nu$, $R_\nu$, and $I$-band data sets assume no color evolution. The differences between these comparisons and the later comparisons that incorporate spectrally derived bolometric corrections afford a measure of the importance of color evolution at late epochs.

3. SN Ia OBSERVATIONS

To perform model-generated energy deposition rate/SN light-curve comparisons, a large collection of SNe Ia observations has been compiled. The principal sources of $B_\nu$, $V_\nu$, $R_\nu$, and $I$-band photometry are seven of the 29 SNe Ia observed by Hamuy et al. (1996) and six of the 22 SNe Ia observed by Riess et al. (1999b). MTL fitted the 10 SNe Ia best observed to very late times. Of those 10 SNe, only six are included in this study (as explained below). These SNe have been supplemented with observations of SN 1995D by Sadakane et al. (1996), SN 1996X by Salvo et al. (2001), SN 1997cn by Turatto et al. (1998), SN 1998bu by Jha et al. (1999), Suntzeff et al. (1999), Garnavich et al. (2000, unpublished), and Cappellaro et al. (2001b, in preparation), and SN 1998de by Modjaz et al. (2001) (SN 1995D and 1996X were also observed by Riess et al. 1999b). Of the 64 observed SNe Ia (29 + 22 + 10 + 3), 22 were included in this study.\footnote{To be included, an SN had to be observed at least once after day 85, with at least one observation within ±20 days of the normalization epoch (explained below), chosen to be 65 days postexplosion. In addition, the SN had to be first observed no later than one week post-B maximum (a requirement relaxed for the SN 1992K because of the undersampling of the subluminous subclass). The SNe Ia that meet these criteria are listed in Table 1. Four SNe Ia from MTL were not included in this study. SNe 1937C and 1972E were not well observed with multiband photometry and were excluded. SN 1993L was discovered more than a week postpeak and was excluded. The late photometry of SN 1989B is being reanalyzed and thus was excluded.\footnote{The SN has been identified as a light echo candidate (Boffi et al. 1999). As published, the late light curve of SN 1989B is more than 1 mag brighter than the suggested models and is the single exception to the trends seen in the other SNe.}

The 22 SNe Ia have been divided into luminosity subclasses: normally luminous, subluminous, and super-

| SN Name | Host Galaxy | $\Delta m_{15}(B)^a$ (mag) | Luminosity Subclass | $M_B^{\text{ph}}$ (mag) | $M_V^{\text{ph}}$ (mag) | $M_R^{\text{ph}}$ (mag) | Photometry References | Spectroscopy References |
|---------|-------------|---------------------------|---------------------|------------------------|------------------------|------------------------|------------------------|------------------------|
| 1986G   | NGC 5128    | 1.73                      | sb                  | -18.1                  | -18.4                  | -18.4                  | 1–3, 5                 | ...                    |
| 1990N   | NGC 4639    | 1.07                      | N                   | -19.8                  | -19.7                  | -19.3                  | 4, 24                  | 7, 8                   |
| 1990O   | PGC 59955   | 0.96                      | N                   | -19.5                  | -19.5                  | -19.0                  | 5                      | ...                    |
| 1991T   | NGC 4527    | 0.94                      | SP                  | -19.6                  | -19.6                  | -19.2                  | 4, 6, 28               | 9, 12                  |
| 1991ag  | IC 4919     | 0.87                      | SP                  | -19.7                  | -19.7                  | -19.3                  | 5                      | ...                    |
| 1991bg  | NGC 4374    | 1.93                      | sb                  | -16.6                  | -17.4                  | -17.8                  | 5, 9–11                | 9, 12                  |
| 1992A   | NGC 1380    | 1.47                      | N                   | -18.8                  | -18.8                  | -18.5                  | 13, 24                 | 14                     |
| 1992K   | ESO 269-57  | 1.93                      | sb                  | ...                    | ...                    | ...                    | ...                   | 5                      |
| 1992al  | ESO 234-69  | 1.11                      | N                   | -19.5                  | -19.5                  | -19.1                  | 5                      | ...                    |
| 1992bc  | ESO 300-9   | 0.87                      | SP                  | -19.6                  | -19.6                  | -19.2                  | 5                      | ...                    |
| 1993H   | ESO 455-66  | 1.69                      | sb                  | -18.7                  | -18.8                  | -18.8                  | 5                      | ...                    |
| 1993ag  | Anonymous   | 1.32                      | N                   | -19.4                  | -19.3                  | -18.9                  | 5                      | ...                    |
| 1994D   | NGC 4526    | 1.32                      | N                   | -19.0                  | -19.0                  | -18.8                  | 5, 6, 15, 16           | 15, 17                 |
| 1995D   | NGC 2962    | 0.99                      | N                   | -19.4                  | -19.3                  | ...                    | 18, 19                 | 20                     |
| 1995E   | NGC 2441    | 1.06                      | N                   | -20.0                  | -19.9                  | ...                    | 18                     | ...                    |
| 1995ac  | Anonymous   | 0.91                      | SP                  | -19.2                  | -19.1                  | ...                    | 18                     | ...                    |
| 1995al  | NGC 3021    | 0.83                      | SP                  | -20.1                  | -20.0                  | ...                    | 18                     | ...                    |
| 1995bd  | UGC 3151    | 0.84                      | SP                  | -19.7                  | -19.9                  | ...                    | 18                     | ...                    |
| 1996X   | NGC 2935    | 1.25                      | N                   | -19.5                  | -19.5                  | ...                    | 18, 21                 | 21                     |
| 1997cn  | NGC 5490    | 1.86                      | sb                  | -17.3                  | -18.0                  | -18.2                  | 22                     | ...                    |
| 1998bu  | M96         | 1.01                      | N                   | -19.5                  | -19.5                  | -18.7                  | 23–26                  | 20                     |
| 1998de  | NGC 5252    | 1.96                      | sb                  | -17.0                  | -17.6                  | -17.8                  | 27                     | 27                     |

\footnote{All $\Delta m_{15}(B)$-values are from Hamuy et al. 1996 and Phillips et al. 1999, except SNe 1997cn and 1998de.\footnote{Absolute magnitudes for SNe in Hamuy et al. 1996 and Riess et al. 1999b surveys have been calculated from extinction estimates of Phillips et al. 1999. Absolute magnitudes for all other SNe were obtained from published photometry. All absolute magnitudes assume $H_0 = 65$ km s\(^{-1}\) Mpc\(^{-1}\).}

REFERENCES. — (1) Phillips et al. 1987. (2) Phillips et al. 1997, unpublished. (3) Cristiani et al. 1992. (4) Lira et al. 1998. (5) Hamuy et al. 1996. (6) Cappellaro et al. 1998, unpublished. (7) Mazzali et al. 1995. (8) Filippenko et al. 1992b. (9) Turatto et al. 1996. (10) Leibundgut et al. 1993. (11) Filippenko et al. 1992a. (12) Ruiz-Lapuente et al. 1993. (13) Suntzeff 1996. (14) Kirshner et al. 1993. (15) Patat et al. 1996. (16) Tanvir et al. 1997, unpublished. (17) Filippenko 1997. (18) Riess et al. 1999 (19) Sadakane et al. 1996. (20) Matheson 2000, unpublished. (21) Salvo et al. 2001. (22) Turatto et al. 1998. (23) Jha et al. 1998 (24) Suntzeff et al. 1999. (25) Garnavich et al. 2000, unpublished. (26) Cappellaro et al. 2001b, in preparation. (27) Modjaz et al. 2001. (28) Gibson & Stetson 2001.
luminous (hereafter these categories will be denoted in figures by “N,” “sb,” and “SP”). The categorization is based upon the $\Delta m_{15}(B)$-values (Phillips 1993) of the SNe. Numerous empirical relations have been derived for SNe Ia by plotting a given variable versus $\Delta m_{15}(B)$. Shown in Figure 2 are the maximum $B$, $V$, and $I$-band absolute magnitudes for 21 of the 22 SNe Ia analyzed in this study, together with 18 others from Hamuy et al. (1996). Early studies assumed a linear relationship between these variables for all SNe Ia. A larger sampling has suggested that all these relations deviate from linearity at $\Delta m_{15}(B) \sim 1.6$ mag. It is unclear whether this deviation is best explained by a continuous quadratic function applicable to all SNe Ia (Phillips et al. 1999) or by two different linear relations, one

13 Of the 29 SNe Ia listed in Hamuy et al. (1996), the figure includes only the 18 SNe with well-defined peak shapes. SN 1992K was discovered too many days after peak to be included in Figure 2, but it is well observed at late times and is used in this work.

The phenomenon studied in this work is the evolution of the light curves at late epochs. For this reason, a relative magnitude scale has been employed, rather than an absolute or apparent magnitude scale. All SNe have been normalized to have zero magnitude at 65 days postexplosion (assuming an 18 day rise time for all subclasses). We make no effort to model the absolute magnitude of individual light curves (i.e., we do not include distance estimates, nor do we attempt absolute bolometric corrections). The reader is referred to the previously mentioned papers that do treat absolute magnitudes of SN Ia models for discussion of the ability of individual models to explain the various luminosity subclasses of SNe Ia. For reference, shown in Table 2 are estimates of the absolute magnitude of the $V$-band peak, as calculated by Höflich & Khokhlov (1996).

The initial motivation for the day 65 normalization date was based upon the suggestion in Pinto & Eastman (2000a) that the photon diffusion timescale becomes negligibly short at roughly that time. As § 4 shows, a high level of homogeneity exists within the multiband photometry of each subclass after day 65. In addition, the greater number of observations between day 45 and day 85 relative to later epochs makes the normalization algorithm perform better at early times. These two factors led us to retain the day 65 normalization date for all data sets, although the model-generated energy deposition rates do not fit the band photometry at day 65 for any band-subclass combination. The normalization has been performed by linear interpolation of all data between day 45 and day 85. For two SNe, only a

### TABLE 2

| Model Name | Mode of Explosion | $M_\text{a}$ ($M_\odot$) | $M_{\text{bol}}(M_\odot)$ | $E_{\text{kin}}$ | $M_V^{\text{peak}}$ (mag) | Reference |
|------------|-------------------|------------------------|--------------------------|-----------------|-----------------------------|-----------|
| W7         | Deflagration      | 1.37                   | 0.58                     | 1.24            | −19.63                      | 1, 5      |
| DD23C      | Delayed detonation| 1.34                   | 0.60                     | 1.17            | −19.2                       | 2         |
| W7DT       | Late detonation   | 1.37                   | 0.76                     | 1.61            | −18.27                      | 3         |
| PDD54      | Pulsed delayed detonation | 1.40 | 0.17 | 1.72 | −18.27 | 4 |
| HED6       | He detonation     | 0.77                   | 0.26                     | 0.74            | −15.63                      | 5         |
| HED8       | He detonation     | 0.96                   | 0.51                     | 1.00            | −19.21                      | 5         |
| HECN       | He detonation     | 1.07                   | 0.72                     | 1.35            | ...                         | 6         |
| ONEMg      | AIC               | 0.59                   | 0.16                     | 0.96            | ...                         | 7         |
| SmallFry   | AIC               | 0.20                   | 0.05                     | 0.32            | ...                         | 8         |
| DET2E2     | Merger detonation | 1.40                   | 0.62                     | 1.33            | −19.41                      | 5         |

REFERENCES. — (1) Nomoto, Thielemann, & Yokoi 1984. (2) Höflich et al. 1998. (3) Yamaoka et al. 1992. (4) Höflich, Khokhlov, & Wheeler 1995. (5) Höflich & Khokhlov 1996. (6) Kumagai & Nomoto 1997. (7) Nomoto et al. 1996. (8) Fryer et al. 1999.
single observation was taken in that interval. For those SNe, the latest pre–day 45 observation was used to perform the interpolation.

By treating all SNe within a given $\Delta m_{15}(B)$ range as a single object, we are assuming homogeneity within each luminosity subclass. The amount of scatter about a template gives some measure of the quality of that assumption, but numerous sources of systematic errors exist to cloud that interpretation. Each SN light curve is measured relative to the host galaxy’s background light, which is unique to that SN. If the SN is near the detectability limit for that observation, the influence of the background subtraction increases in importance. The irregularity of the sampling means that highly uncertain observations are mixed throughout every epoch of the late light curves. Similarly, different telescopes, filters and detectors were used to produce this data set, introducing additional systematic differences between individual data points. As was shown by Suntzeff (1999), observations of the same SN by the same observer at the same site with the same class telescope can yield different photometry. The differences were found to be in excess of the quoted uncertainties. Suntzeff showed that in this optimal case, the “instrumental uncertainty” was on the order of 0.06 mag for the $V$ band during the day 60–day 75 epoch. In the case of this mixed data set, the uncertainties are likely to be larger. Errors in this work were also introduced by the fitting algorithm, which fitted the individual light curves to the estimated day 65 magnitude.

All errors discussed above have been related to estimates of the relative magnitude. Because SNe are always detected at some time after the explosion, the explosion date is also somewhat uncertain. Two factors may influence uncertainties in the explosion date: uncertainty of a subclass rise time to peak and uncertainty of the peak date. For this work, all SNe were assumed to rise to peak $B$ magnitude in 18 days regardless of the luminosity subclass. To minimize the effect of peak-date uncertainty, only SNe first observed no later than a week after maximum light were used (with the exception of SN 1992K). The determination of the peak date depends upon template fitting, so peak-date uncertainties are only relative to the template used. SNe discovered before $t_{\text{pl(max)}}$ typically have peak date uncertainties of $\pm 1$ day. SNe discovered postpeak have larger uncertainties. Nonetheless, because the timescales involved in this work are on the order of tens of days, uncertainties on the order of a few days will not significantly alter these results.

4. RESULTS

4.1. $V$ Band

The 22 SNe included in this study are shown fitted (by eye) with the delayed-detonation, CM model DD23C in Figure 3. All 22 SNe have been normalized at day 65. Three tendencies are apparent in the data. First, within each subclass the data show remarkable homogeneity. The subclasses are defined by differences in the early light-curve shape, but after day 65 there is no evidence of variations within each subclass. Second, the normally luminous and superluminous data seem to evolve similarly, while the subluminous subclass continues to fall more steeply (recall that a steep decline from peak defines this subclass). Third, the separation between the normally luminous/superluminous and the subluminous subclasses far exceeds the scatter within the subclasses. This argues against a continuous transition between the subluminous and normally luminous subclasses. Unfortunately, the subluminous subclass is undersampled, so many more subluminous SNe have to be observed before we can address whether there exists an absolute separation of subclasses.

After about day 80 the normally luminous and superluminous subclasses seem to be explainable by this model, assuming radial escape. By contrast, the subluminous subclass cannot be explained by either magnetic field scenario. To improve the visualization of the day 40–day 120 normally luminous and superluminous data, in the inset of Figure 3 we show the data as residuals relative to the model curve. The similarity between the normally luminous and superluminous data sets is apparent. Also apparent in the inset is the failure of the model light curves to fit the $V$-band data in detail until after about day 120. These results are not specific to the delayed-detonation, CM model DD23C. Shown in Figure 4 are six models suggested to explain normally luminous and superluminous SNe, shown in the “delta magnitude” format. The models are defined in Table 2. All model light curves show the same fundamental structure, with the models fitting the data after about day 170 and suggesting positron escape. The CM models fit the normally luminous data better than does the SC–mass model, but the improvement is modest. As was discussed in

---

14 The delta magnitude format shows the residuals of the data and model-generated light curves to the instantaneous deposition approximation, in units of magnitude.
MTL, the superluminous model light curves are similar both to other superluminous SN models and to normally luminous, CM model light curves. We assert that the 16 normally luminous and superluminous SNe do not need to be differentiated into distinct subclasses after day 60. We further assert that, if the $V$-band emission scales with the bolometric emission to the level of a few tenths of a magnitude, the late emission from all 16 SNe can be suitably explained with a single light curve featuring positron escape and that CM, SC-mass, and merger explosions can all explain these data.

It is apparent from Figure 3 that the subluminous subclass differs considerably from the normally luminous and superluminous subclasses. MTL concluded that none of the models they tested could explain the evolution of the light curves from day 60 to day 560. One interpretation of that result is a rejection of both the CM and the SC-mass models tested. A different interpretation would be the failure of the assumption that the energy deposition rate scales with the $V$ band during that epoch. Figure 5 shows five subluminous models fitted to the subluminous subclass data. The models are normalized to fit the data at a later epoch (about day 170). It is clear from the figure that none of the models can explain the $V$-band data before day 150.\(^\text{15}\) After day 150, the $V$-band data can be suitably explained by all models if positron escape is assumed.\(^\text{16}\) This latter interpretation implies that the energy deposition rate scaling with the $V$ band occurs later for the subluminous subclass than for the other subclasses. For this interpretation to be correct, there must be an explanation consistent with the spectral observations, which suggest that subluminous SNe Ia enter the nebular phase earlier than normally luminous or superluminous SNe Ia (Mazzali et al. 1997).

4.2. BVRI Bands

In the previous section, we fitted model-generated energy deposition rates to $V$-band data. That procedure relies upon the assertion that the $V$ band traces the bolometric luminosity. For the normally luminous/supeluminous data set, the data are approximately fitted with the models, suggesting a validation of that assertion. By contrast, for the subluminous data set the models could not fit the data until a later epoch. All SNe Ia used in this study were also observed in the $B$, $R$, and $I$ bands. By independently fitting these data sets to the model-generated energy deposition rates, we further explore the nature of the late-time emission from SNe Ia.

Shown in Figure 6 are the $BVRI$ data sets for SNe Ia fit to the model W7. Within each subclass the data have been normalized to day 65. Each subclass has then been independently fitted to the model light curves. For all four photometric bands, the normally luminous and superluminous light curves are similar. The $B$-band data for the normally luminous and superluminous SNe Ia deviate considerably from the model before day 100, but by about day 170 they roughly scale with the energy deposition rate. The $B$-band data for the subluminous subclass differ from the normally luminous and superluminous subclasses early but seem

\(^{15}\) The bottom panel is an AIC model that ejects 0.2 $M_\odot$ of material. The model was created by scaling ONeMg to 0.2 $M_\odot$. This model is included upon the suggestion of Fryer, Benz, & Herant (1996) and Fryer et al. (1999) that AICs may explain subluminous SNe Ia. Even at this extremely low mass, the early escape of positrons is not enough to reproduce the steepness of the day 65–day 170 light curve.

\(^{16}\) It is important to note that the range of allowed ionizations leads to fairly thick curves for low-mass models, exaggerating the visual impression of their ability to explain the data. A treatment of the level of ionization would reduce the range to a single curve.
The interpolation was performed in two steps. The shape of the interpolated portion was determined from the two complete spectra adjacent in time. That shape was then spliced to the existing portion.

The interpolation was performed in two steps. The shape of the interpolated portion was determined from the two complete spectra adjacent in time. That shape was then spliced to the existing portion.

Fig. 6—BVRI-band light curves of 22 SNe Ia fitted with model-generated energy deposition rates from the CM model W7. Models and data have been transformed to delta magnitude format. Symbols for the data points are as in Fig. 4. The SB luminosity subclass follows a different early evolution than the N and SP subclasses in the B and V bands, but all three subclasses are similar in the R and I bands. For all SNe Ia, all four bands are approximated by the model fit after day 170, if positron escape is assumed.

Similar at late times. Perhaps the most striking results are in the R and I bands, where the three subclasses are quite similar. We argue that the differences between the late evolution of the B- and V-band data do not carry over to the longer wavelengths. The model fits initially deviate from the R- and I-band data for all three subclasses but then converge upon the model curve by about day 170. The convergence in the I band is less certain because of scatter.

It is interesting to note that the onset of the energy deposition scaling with the photometry (about day 170) occurs later than the transition from photospheric continuum emission to nebular emission (about day 60) for all three SN Ia subclasses and all four photometric bands. To determine whether this delay is explainable as a consequence of color evolution, we produce spectral templates for normally luminous/superluminous and subluminous SNe Ia. The templates have been created from a collection of SN Ia spectra: 1994D (Patat et al. 1996; Turatto et al. 2000, unpublished; Filippenko 1997), 1991T (Filippenko et al. 1992b), 1996X (Salvo et al. 2001), 1991bg (Turatto et al. 1996; Ruiz-Lapuente et al. 1993), 1987L (Ruiz-Lapuente et al. 1993), 1994ae (Bowers et al. 1997), 1998de (Modjaz et al. 2001), 1998bu (Jha et al. 1999; Matheson 2000, unpublished), 1995D (Matheson 2000, unpublished), 1981B (Branch et al. 1983), 1984A (Branch 1987), 1991F (Gómez & López 1995), 1992A (Kirshner et al. 1993). We include all emission within the 3500–9700 Å wavelength range and ignore all emission outside of this range. Spectra that do not span this range have been linearly interpolated from earlier and later spectra. The spectral sequences for a sampling of each subclass are shown in Figures 7 and 8. From these templates, we have determined the evolution of the fraction of the energy emission in the 3500–9700 Å wavelength range detected by each band. The evolution of this fraction is shown in Figure 9 for normally luminous and superluminous data set. The V band samples a roughly constant fraction of the spectral range, in agreement with previous assertions that the V band scales with the bolometric luminosity. Shown in Figure 10 are the B-, V-, R-, and I-band data fitted to the model W7, after bolometric corrections were derived from these fractions. The data for all four bands are suitably explained by the energy deposition rates of the model if positron escape is assumed. Before about day 60, the B, V, and I data vary dramatically from the energy deposition rates. This would be consistent with the decrease to negligible values of the photon diffusion timescale, as suggested by Pinto & Eastman (2000a). The correction lessened but did not completely remove the residuals from the B- and V-band data during the day 60–day 170 epoch. It is unclear whether the residuals remain because of a modest failure of this relatively crude

Contardo et al. (2000) arrived at a similar result.

Fig. 7—Sequence of spectra of normally luminous and superluminous SNe. All spectra have been offset by an arbitrary constant. Incomplete spectra are denoted with an asterisk. It is clear from these spectra that the emission within this wavelength range experiences a blueward shift. Transmission efficiencies for the B, V, R, and I filters are shown above the spectra for reference.

Fig. 8—Sequence of spectra of subluminous SNe. As in Fig. 7, all spectra have been offset by an arbitrary constant, and incomplete spectra are denoted with an asterisk (*). This spectral sequence differs considerably from that in Fig. 7, most notably because of the peak at 7300 Å and the persistence of emission redward of 8000 Å. Transmission efficiencies for the B, V, R, and I filters are shown above the spectra for reference.

The interpolation was performed in two steps. The shape of the interpolated portion was determined from the two complete spectra adjacent in time. That shape was then spliced to the existing portion.

The interpolation was performed in two steps. The shape of the interpolated portion was determined from the two complete spectra adjacent in time. That shape was then spliced to the existing portion.

The interpolation was performed in two steps. The shape of the interpolated portion was determined from the two complete spectra adjacent in time. That shape was then spliced to the existing portion.

The interpolation was performed in two steps. The shape of the interpolated portion was determined from the two complete spectra adjacent in time. That shape was then spliced to the existing portion.
bolometric correction calculation or because this treatment has ignored some physical phenomenon.

The application of these corrections essentially creates bolometric light curves from each photometric band. A single bolometric light curve for normally luminous and superluminous SNe Ia was generated by combining the four curves shown in Figure 10 after weighting each curve according to the photometry errors. The resulting bolometric light curve can be compared with model-generated light curves. These comparisons, shown in Figure 11, exhibit the same tendencies seen in the V band: the energy deposition rates for all four models are consistent with the data, and positron escape is suggested. These curves differ slightly from the bolometric light curve derived by Contardo, Leibundgut, & Vacca (2000) from much of the same data. That study was primarily concerned with emission near the luminosity peak and assumed constant bolometric corrections at late times (t \( \geq 130 \) days). Because we have shown that some color evolution occurs during the day

60–day 200 time period, we assert that our bolometric light curve is more accurate at late times than the light curve from Contardo et al. (2000). Although bolometric light curves include information from four photometric bands rather than simply from the V band, the V band is the best observed. Thus, we present the bolometric light curve primarily to demonstrate that conclusions derived from studies of the V-band shape are valid.

There are few nebular spectra for subluminous SNe Ia, so for this subclass the estimates of the fraction of the 3500–9700 Å wavelength range sampled by each photometric band are very crude, and they are undersampled after day 150 (Fig. 12). This is problematic because, as shown in Figure 6, the day 100–day 200 time span is a critical transitional epoch. Nonetheless, as shown in Figure 13, the B-, V-, R-, and I-band data are also fairly sparse and can be roughly explained with the model PDD54, after bolometric corrections are applied. All four bands fit the energy deposition rates better with the correction, as seen by comparison with Figure 6. There are large residuals in the V and I bands before about day 50. This is likely due to photon diffusion delays. It is evident in Figure 13 that the light curves of subluminous SNe Ia are consistent with
model-generated energy deposition rates. If no further color evolution occurs after day 200, then the comparisons shown in Figure 5 are valid and the V-band light curves show evidence of positron escape. More spectral and photometric data of subluminous SNe Ia are needed to further the understanding of this epoch. Because of the crudeness of the bolometric corrections, a bolometric light curve was not generated for the subluminous subclass.

The success of the bolometric corrections in reducing the residuals during the day 60–day 170 time span suggests the existence of an epoch during which optical emission is instantaneously recycled but the SN color continues to evolve. A possible explanation for this color evolution is the decay of 56Co to 56Fe. It is during the day 65–day 170 epoch that the daughter becomes the dominant species in that decay. As shown by both Liu et al. (1997a, 1997c) and Bowers et al. (1997), cobalt emission dominates the wavelength ranges observed with the R and I bands. Because 56Co decays to 56Fe, these bands would fade faster than the energy deposition rate because of color evolution until late times, when most cobalt has decayed and iron and stable nickel dominate the spectrum in that wavelength range. In the V-band wavelength range, both Co and Fe lines are present, and the bolometric correction would change only slightly during the transition. The B band may brighten because of the increased emission from the many [Fe II] lines from 446 to 456 nm. This explanation can be tested through comparisons of model-generated spectra with observations made during this epoch. It is unclear whether this explanation can account for the differences between the light curves for the normally luminous/superluminous SNe Ia and those for the subluminous SNe Ia.

5. DISCUSSION

Two tasks comprised this work. The first task was the compilation of a data set of B, V, R, and I photometry of type Ia SNe divided into subclasses and the development of bolometric correction factors for each band. The second task was the generation of late-time light curves from SN Ia models and the fitting of these models to the compiled data set. Certain findings can be derived from this study independent of the model fitting and are worthy of mention. We have demonstrated that there is order to the late light curves. The late B- and V-band light curves of 16 normally luminous and superluminous SNe follow a similar evolution, while those of six subluminous SNe follow a different evolution. By contrast, the late R- and I-band light curves of all 22 SNe Ia follow a similar evolution. The normally luminous/superluminous subclasses have virtually identical light curves, although they span more than half of the $\Delta m_{15}(B)$ range of SNe in this study. The B- and V-band light curves of the subluminous SNe seem to require a distinct subclass. Whether there are in fact SNe Ia that connect them to normally luminous objects is an important question. This question can only be answered by observational campaigns that focus upon monitoring SNe that span the range of $\Delta m_{15}(B)$-values.

Comparisons of model-generated energy deposition rates with photometry in the B, V, R, and I bands reveal three epochs. There is an early epoch (through day 60), during which energy deposition–photometry comparisons are invalid, presumably because of the time delay between the deposition of energy and the emergence of the resultant optical emission. That epoch is followed by an intermediate epoch (day 60–day 170), during which the bolometric light curve is fitted by the energy deposition rate but color evolution must be addressed for individual photometric bands to be fitted by the energy deposition rate. This epoch is followed by a late epoch (starting with day 170) during which the bolometric corrections are roughly constant and each individual photometric band can be fitted by the energy deposition rate if positron escape is allowed for. These epochs exist for both the normally luminous/superluminous and the subluminous subclasses. The bolometric corrections during the intermediate epoch are better defined for the normally luminous/superluminous SNe Ia than for the subluminous SNe Ia; the latter corrections are preliminary.

Collectively, the light curves of SNe Ia after day 60 suggest that the interactions of the products of the $^{56}Co \rightarrow ^{56}Fe$ decay with the ejecta can explain the energy deposition without any additional energy deposition source. Positrons are seen to escape the ejecta in quantity for all SNe Ia during the late epoch. These findings hold for CM, SC–mass, merger, and AIC models equally. The model independence of these results does not imply that the late emission from SNe Ia cannot probe the progenitor. The challenge for NLTE radiation transport calculations is to reproduce the spectra during this epoch.

There are two ramifications of positron escape from SN Ia ejecta that warrant further discussion. First, nebular spectra have been used to estimate the $^{56}Ni$ production in SNe Ia (Ruiz-Lapuente & Filippenko 1996; Bowers et al. 1997) and to differentiate between CM and SC–mass models (Liu et al. 1997a, 1997b, 1998). In all these studies, instantaneous positron energy loss was assumed. By day 300, the energy deposition is dominated by positron slowing, and a substantial fraction of those positrons are expected to escape the ejecta in the radial scenario. Even positrons that do not escape the ejecta diffuse from the location of their creation. In light of this and other recent studies, nebular spectrum studies should be calculated with realistic positron transport. Second, positrons that escape the SN Ia ejecta are thought to survive nonthermally on timescales of $10^5$ yr or more (Chan & Lingenfelter 1993; Guessoum, Ramaty, & Lingenfelter 1991). The collective positron contributions from SNe Ia, as inferred from extragalactic SN rates, are sufficient to generate a large fraction...
of the 511 keV positron annihilation radiation observed by the CGRO/OSS, SMM, and TGRS gamma-ray telescopes (MTL; Milne et al. 2000). The degree of dominance is enough that accurate characterization of positron annihilation radiation will trace recent SN Ia activity in the Galaxy.

Light echoes have been detected from two SNe Ia, 1991T and 1998bu. In addition, Boffi, Sparks, & Macchetto (1999) have identified SN 1998B as a light echo candidate. Of all SNe Ia observed after day 300, these three are the only SNe to remain significantly brighter than those in this work. Because light echoes are currently being used as geometric distance indicators, this work suggests that the templates shown here may be used to locate light echoes (Sparks et al. 1999).

There remain incomplete aspects to this study. More SNe Ia must be monitored to reduce gaps in observations and to determine the late behavior of more SNe Ia along the $\Delta m_{15}(B)$ sequence. The exact nature of the transition from the onset of instantaneous recycling to the cessation of color evolution must be better observed spectrally and in each photometric band, particularly for subluminous SNe Ia. These unexplained aspects underscore the fact that much is to be learned about the physics of Type Ia SNe from late observations.

We thank P. Höflich for ongoing access to SN models and for discussions relating to radiation transport through SN ejecta. We thank K. Nomoto for access to SN models. We thank M. Turatto, E. Cappellaro, P. Garnavich, and S. Jha for access to SN photometry and spectra. We also thank T. Matheson, R. Lopez, and P. Meikle for SN spectra.

REFERENCES

Aldering, G., Knop, R., & Nugent, P. 2000, AJ, 119, 2110
Axelrod, T. S. 1980, Ph.D. thesis, Univ. California, Santa Cruz
Baron, E., Hauschildt, P. H., Nugent, P., & Branch, D. 1996, MNRAS, 283, 297
Boffi, F., Sparks, W. B., & Macchetto, F. D. 1999, A&AS, 138, 253
Bowers, E. J. C., Meikle, W. P. S., Geballe, T. R., Walton, N. A., Pinto, P. A., Dhillon, V. S., Howell, S. B., & Harrop-Allin, M. K. 1997, MNRAS, 290, 663
Branch, D. 1987, ApJ, 316, L81
Branch, D., Doggett, J. B., Nomoto, K., & Thielemann, F.-K. 1985, ApJ, 294, 619
Branch, D., Lacy, C. H., McCall, M. L., Sutherland, P. G., Uomoto, A., Wheeler, J. C., & Wills, B. J. 1985, ApJ, 270, 123
Burns, A. & The, L.-S. 1990, ApJ, 360, 626
Cappellaro, E., Mazzali, P., Benetti, S., Danziger I. J., Turatto, M., Della Valle, M., & Patat, F. 1997, A&A, 328, 203 (CAPP)
Cappellaro, E., Patat, F., Mazzali, P., Benetti, S., Danziger, I. J., Pastorello, A., Rizi, L., Salvo, M., Turatto, M. 2001a, ApJ, 549, L215
Cappellaro, E., et al. 2001b, in preparation
Chan, K.-W., Lingenfelter, R. E. 1993, ApJ, 405, 614
Colgate, S. A., Petschek, A. G., & Kriss, J. T. 1980, ApJ, 243, L81
Contrado, G., Leibundgut, B., & Vaccarino, D. W. 2000, A&A, 359, 876
Cristiani, S. et al. 1992, A&A, 259, 63
Filippenko, A. V. 1997, in Thermonuclear Supernovae, ed. P. Ruiz-Lapuente, R. Canal, & J. Isern (NATO ASI Ser. C, 486) (Dordrecht: Kluwer), 1
Filippenko, A. V., et al. 1992a, AJ, 104, 1543
— 1992b, ApJ, 384, L15
Fryer, C., Benz, W., & Herant, M. 1996, ApJ, 460, 801
Fryer, C., Benz, W., Herant, M., & Colgate, S. A. 1996, ApJ, 461, 802
Gibson, B., & Stetson, P. B. 2001, ApJ, 547, L103
Gómez, G., & López, R. 1999, AJ, 109, 737
Gossez, H., Ramanay, R. & Lingenfelter, R. E. 1991, ApJ, 378, 170
Hamuy, M., Phillips, M. M., Schommer, R. A., Suntze†, N. B., Maza, J., & Avilés, R. 1996, AJ, 112, 2391
Höflich, P., 1995, ApJ, 443, 89
Höflich, P., & Khokhlov, A. 1996, ApJ, 457, 500
Höflich, P., Khokhlov, A., & Wheeler, J. C. 1995, ApJ, 444, 831
Höflich, P., Khokhlov, A., Wheeler, J. C., Phillips, M. M., Suntze†, N. B., & Hamuy, M. 1996, ApJ, 472, L81
Höflich, P., Khokhlov, A., & Thielemann, F.-K. 1999, ApJ, 495, 617
Jeffery, D. J., Leibundgut, B., Kirshner, R. P., Benetti, S., Branch, D., & Sonneborn, G. 1992, ApJ, 397, 304
Jha, S. et al. 1999, ApJS, 125, 73
Kirshner, R. P., et al. 1993, ApJ, 415, 589
Kumagai, S., & Nomoto, K. 1997, in Thermonuclear Supernovae, ed. P. Ruiz-Lapuente, R. Canal, & J. Isern (NATO ASI Ser. C, 486) (Dordrecht: Kluwer), 515
Leibundgut, B. 2000, A&A Rev., 10, 179
Livio, M. 2000, in Greatest Explosions Since the Big Bang, ed. M. Livio, N. Panagia, & K. Sahu (Cambridge: Cambridge Univ. Press), in press (astro-ph/0005344)
Timmes, F. X., Woosley, S. E., Hartmann, D. H., & Hoffman, R. D. 1996, ApJ, 464, 332
Turatto, M., Benetti, S., Cappellaro, E., Danziger, I. J., Della Valle, M., Gouiffes, C., Mazzali, P. A., & Patat, F. 1996, MNRAS, 283, 1
Turatto, M., Piemonte, A., Benetti, S., Cappellaro, E., Mazzali, P. A., Danziger, I. J., & Patat, F. 1998, AJ, 116, 2431
Watanabe, K., Hartmann, D. H., Leising, M. D., & The, I.-S. 1999, ApJ, 516, 285
Yamaoka, H., Nomoto, K., Shigeyama, T., & Thielemann, F.-K. 1992, ApJ, 393, 155