Positron Escape from Type Ia Supernovae

P.A. Milne\(^1\)\(^2\)
Naval Research Laboratory, Code 7650, Washington, DC 20375

L.-S. The, M.D. Leising
Department of Physics and Astronomy
Clemson, S.C., 29634-1911

Received _______________; accepted ________________

\(^1\)NAS/NRC Resident Research Associate.

\(^2\)Much of this work was performed at Clemson University.
ABSTRACT

We generate bolometric light curves for a variety of type Ia supernova models at late times, simulating gamma-ray and positron transport for various assumptions about the magnetic field and ionization of the ejecta. These calculated light curve shapes are compared with light curves of specific supernovae for which there have been adequate late observations. From these comparisons we draw two conclusions: whether a suggested model is an acceptable approximation of a particular event, and, given that it is, the magnetic field characteristics and degree of ionization that are most consistent with the observed light curve shape. For the ten SNe included in this study, five strongly suggest $^{56}$Co positron escape as would be permitted by a weak or radially-combed magnetic field. Of the remaining five SNe, none clearly show the upturned light curve expected for positron trapping in a strong, tangled magnetic field. Chandrasekhar mass models can explain normally, sub-, and super- luminous supernova light curves; sub-Chandrasekhar mass models have difficulties with sub- (and potentially normally) luminous SNe. An estimate of the galactic positron production rate from type Ia SNe is compared with gamma-ray observations of Galactic 511 keV annihilation radiation. Additionally, we emphasize the importance of correctly treating the positron transport for calculations of spectra, or any properties, of type Ia SNe at late epochs ($\geq 200$ d).

Subject headings: supernovae:general-gamma rays:observations, theory
1. INTRODUCTION

Many years of study of the light curves and spectra of type Ia supernovae have revealed that a thermonuclear runaway induced by accretion on a white dwarf of $\sim 1 \, M_\odot$ (Hoyle & Fowler 1960) produces the energy to eject the entire star at $\sim 10,000 \, \text{km s}^{-1}$ and synthesizes $\sim 0.1-1.0 \, M_\odot$ of radioactive $^{56}\text{Ni}$. Prior to the maximum luminosity, the ejecta are opaque and both the explosion energy and the energy from the $^{56}\text{Ni} \rightarrow ^{56}\text{Co} \rightarrow ^{56}\text{Fe}$ decays are deposited in and diffuse outward through the ejecta. After the bolometric light curve reaches its peak, the luminosity approaches the instantaneous decay power (Arnett 1980; 1982) and the luminosity decline follows the decay of $^{56}\text{Co}$, with $\gamma$-ray scattering and absorption dominating energy deposition. Later, due to expansion, $\gamma$-ray optical depth decreases and the bolometric light curve decline becomes steeper than the $^{56}\text{Co}$ decay. Around $t \geq 200^d$, almost all $\gamma$-ray photons directly escape the ejecta and positrons from the decay of $^{56}\text{Co}$ provide the main source of energy deposition into the ejecta. At this time, the light curve settles onto another, lower, $^{56}\text{Co}$ decay curve. Beyond this time the light curve evolution depends on the details of positron transport and energy loss. Here we calculate energy deposition in type Ia supernovae (SNe Ia) for $t \geq 60^d$, when the photon diffusion time is short and the bolometric luminosity is almost entirely due to gamma-ray and positron energy loss processes.

There has been significant progress in understanding the physics of the early type Ia light curves. Detailed radiation transport and expansion opacity computations have reproduced observations of the bolometric and filter light curves (i.e., Pinto & Eastman 1998; Höflich, Müller, & Khokhlov 1993; Woosley & Weaver 1986). It is clear that the light curve’s rapid early evolution is due to the explosion of a low mass compact object with a short radiative diffusion time (Arnett 1982; Pinto & Eastman 1998). The secondary IR-maximum is the result of a photospheric radius that continues to expand.
after visual maximum. The differences in pre-maximum rise-times among observed SNe can be explained in model-dependent terms as due to the differences in a transition from a deflagration flame to a detonation. The connections among peak luminosity, light curve width, and post-maximum slope with the ejecta mass, $^{56}$Ni location, kinetic energy of explosion, and opacity are explored in an elegant paper by Pinto & Eastman (1998). Comparisons between early observed light curves and many various theoretical models have been made extensively in recent years (Höflich, Wheeler, & Thielemann 1998; Höflich et al. 1996; Höflich & Khokhlov 1996 (hereafter HK96)). We take the results of these works as given and extend the comparison of the models and observations to later times.

For a few bright SNe Ia in the past half-century, good light curves beyond $t \geq 200^d$ have been obtained and studied. The first work that utilized the information from late light curves was done by Colgate, Petschek, & Kriese (1980). They showed that the late photographic and B band light curves of SN 1937C & SN 1972E can be explained with positron kinetic energy deposition from $^{56}$Co decays, as suggested by Arnett (1969). Recently Colgate (1991, 1997) analyzed late light curves with positron transport to infer the ejecta mass. They found that ejecta somewhat transparent to positrons was required to fit observed light curves. Cappellaro et al. (1997) (hereafter CAPP) studied the influence of the mass of ejecta and the total mass of $^{56}$Ni on SN Ia light curves, and concluded that the fraction of positron energy deposition varies among the five SNe Ia they analyzed, from complete transparency to a complete trapping of the positrons. Ruiz-Lapuente & Spruit (1998) (hereafter RLS) studied the effects of magnetic field geometry and magnitude in exploding white dwarfs to explain observed SNe Ia bolometric light curves. They found that the SN 1991bg magnetic field was weak ($\leq 10^3 G$), while for SN 1972E a full trapping of positrons by a tangled magnetic field in a Chandrasekhar mass model was required.

In addition to furthering our understanding of SNe Ia, we are motivated by the
possibility that the Galactic diffuse 511 keV emission might be due to the annihilation of positrons that escape from SNe Ia, in addition to other possible sources such as core-collapse SN radioactivity and compact objects. The long lifetime of energetic positrons in the ISM ($10^3$-$10^7$ yrs) would mean that positrons from many SNe Ia would appear as a diffuse component of the 511 keV line emission. Chan & Lingenfelter (1993) (hereafter CL) calculated the number of surviving positrons from type Ia supernova models for different magnetic field assumptions. Combining their positron yields with supernova rate estimates, they suggested that type Ia SNe could provide from an insignificant to a dominant contribution to the observed diffuse Galactic annihilation radiation flux – depending on the magnetic field geometry. Average escape of a few per cent of $^{56}$Co positrons are necessary to contribute to the Galactic emission, i.e., $\geq 50\%$ of those emitted after one year would have to escape. If the escapees take a significant fraction of their kinetic energy with them, we might be able to see the power deficit in the measured light curves. Thus we hope to use observed light curves to determine the SNe Ia contribution to Galactic positrons and obtain information about the magnetic fields in SNe Ia.

Because of the variety of observed SN Ia properties and numerous physical details that remain uncertain, there are many possible models allowed (for a review see Nomoto et al. 1996). We do not try to make judgements among them. We calculate the late bolometric light curves of deflagration, delayed detonation, pulsed-delayed detonation, He detonation, and accretion-induced collapse (AIC) models for comparison with observed light curves. For each observed SN we consider the model(s) suggested by other authors to agree with observations near maximum light. We begin by fitting each model to the observations (to the inferred bolometric light curve when available) in the interval 100–200 days, when gamma-ray energy deposition is still important. We then follow each model to later times for various choices of magnetic field configuration and assumed ionization state of the ejecta, and compare the calculated power deposited to the observed light curves.
In addition to the specific light curve consequences of positron transport we examine some more generic features of the late light curves. We show that the light curve decline rate between 60 and 200 days after the explosion can be used to clarify total ejecta mass and expansion velocity of the supernova models. We find that the transition time between the gamma-ray and positron dominated phases is a useful diagnostic to measure the ejecta mass. In addition, the slope of the light curve at $t \geq 200$ days is a good indicator of the magnetic field configuration in the ejecta. As a baseline, we compare the calculated light curves from positron transport with the light curve that results from the immediate, in-situ kinetic energy deposition assumption, which has been typically assumed in early light curve calculations.

The physics of energy deposition in type Ia SNe is discussed in section 2, followed by a discussion of the strength and geometry of the magnetic field in the post-explosion ejecta. Our bolometric light curves for both turbulent and radial field geometries are shown and described in Section 3 for the various models used in our study. The issues confronting fitting model generated light curves to actual observations are discussed in section 4. In Section 5, we combine model predictions with SN data to fit a few of the best observed SNe. We conclude with Section 6 in which we use positron yields from our models to estimate the type Ia contribution to the observations of 511 keV annihilation radiation in the Galaxy.

2. Energy Deposition in SN Models

The $^{56}$Ni $\rightarrow$ $^{56}$Co ($\tau \sim 8.8^d$) decay proceeds via electron capture (100%) and produces photons and neutrinos. The line photons have energies between 0.16 and 1.56 MeV, with a mean energy in photons of 1.75 MeV per decay. The $^{56}$Co $\rightarrow$ $^{56}$Fe ($\tau \sim 111^d$) decay proceeds 81% of the time via electron capture and 19% via positron emission ($\beta^+$ decay). The line photons have energies between 0.85 and 3.24 MeV, with mean energy in photons
per decay of 3.61 MeV. Segre (1977) derived the distribution of positron kinetic energy (which is shown in figure 25). The mean positron kinetic energy is 0.63 MeV, so when multiplied by the branching ratio 0.19, the mean positron energy per decay is 0.12 MeV. The ratio of the mean photon energy to the mean positron kinetic energy is then $\sim 30$. The photon luminosity will dominate until the deposition fraction for positrons ($f_{e^+}$) is $\sim 30$ times larger than the deposition fraction for photons ($f_\gamma$). The energy deposition from both gammas and positrons depend upon two factors; how much material must be traversed enroute to the surface, and the interaction cross-sections. The transport of gamma rays and positrons will be developed separately.

2.1. Gamma-Ray Transport

The gamma-line photons from the decays of $^{56}\text{Ni} \rightarrow ^{56}\text{Co} \rightarrow ^{56}\text{Fe}$ are mostly Compton scattered to lower energy during the early phases of the Type Ia event. These photons then escape as X-ray continuum or are absorbed by material in the ejecta via the photo-electric effect. Due to the supernova expansion, the gamma-line optical depth decreases, becoming low enough at late-times that most gamma-line photons escape directly. In calculating the energy deposition and the energy escape fraction of the photon energy created by the radioactive decays, we simulate the scatter adopting the prescription of Podznyakov, Sobol, & Sunyaev (1983). A detailed description of the Monte Carlo algorithm and its application in calculating the spectra and bolometric light curves of SN1987A and type Ia supernovae have been presented by The, Burrows, & Bussard (1990) and Burrows & The (1990).

Figure 1 shows the fraction of the total decay energy that escapes directly as gamma-lines and emerges as X-ray continuum ($f_{\gamma+X}$) as well as the fractions deposited by scattering ($f_{\text{scat}}$) and photoelectric absorption ($f_{PE}$) as functions of time for model W7 (Nomoto, Thielemann & Yokoi 1984), which we use for illustration here. The solid
curve labeled with \( f_{\text{dep}} = f_{\text{scat}} + f_{\text{PE}} \) is the total gamma-ray energy deposition fraction. Scattering dominates over photoelectric absorption at all times, the photoelectric absorption becoming relatively less important as there become fewer multiply scattered photons at late times. The overall photon deposition fractionscales roughly as \( t^{-2} \), reflecting the time dependence of the column depth to the surface from any location in the ejecta.

2.2. Positron Transport

The cross sections for the various modes of positron annihilation are strongly energy-dependent and favor low energies. Energetic positrons will move through the ejecta until slowed to thermal velocities and then quickly annihilate.\(^3\) Five energy-loss mechanisms were included: ionization and excitation of bound electrons, synchrotron emission, bremsstrahlung emission, inverse Compton scattering, and plasma losses. The first four are described in detail in CL. We include these processes in a calculation of model W7, first assuming a uniformly 1\% ionized medium (i.e., 0.01 free electrons per nucleus) and then a uniformly triply ionized medium. The results, shown in figure 2, support CL’s conclusion that for low ionization, the interactions with bound electrons dominate the energy loss. For higher ionization, we find that plasma energy losses must be included. Regardless of the ionization, processes other than ionization and excitation and plasma losses can be ignored.

The ionization and excitation energy loss rate used is (Heitler 1954; Blumenthal & Gould 1970; Gould 1972; Berger & Seltzer 1954),

\(^3\)The lifetime of positrons once thermalized is small compared to the slowing time and to the decay timescale, so for this study we set it equal to zero.
\[
\frac{dE}{d\xi}_{ie} = -\frac{4\pi r_0^2 m_e c^2 Z_B}{\beta^2 A m_n} \left[ \ln \left( \frac{\sqrt{\gamma - 1} \gamma \beta}{T} \right) + \frac{1}{2} \ln 2 \right] \\
-\frac{\beta^2}{12} \left( \frac{23}{2} + \frac{7}{\gamma + 1} + \frac{5}{(\gamma + 1)^2} + \frac{2}{(\gamma + 1)^3} \right),
\]

(1)

where \( E \) is the positron’s kinetic energy, \( r_0 \) is the classical electron radius, and \( m_e \) and \( m_n \) are the electron and atomic mass unit masses respectively. \( Z_B \) and \( A \) are the effective nuclear charge and atomic mass of the ejecta. \( \bar{T} \) is the effective ionization potential and is approximated by Segre (1977) and by Roy & Reed (1968) as,

\[
\bar{T} = 9.1Z \left( 1 + \frac{1.9}{Z^2} \right) eV.
\]

(2)

The plasma energy loss was described by Axelrod (1980). The formula is the same as ionization and excitation, except \( \bar{\hbar}\omega_p \) is inserted in the calculation of the maximum impact parameter \( (b_{\text{max}}) \) rather than the mean ionization potential \( (\bar{T}) \), and \( \chi_e \), the number of free electrons per nucleus (hereafter ionization fraction) is used rather than \( Z_B \). Thus, \( (Z_B + \chi_e) \cdot n = Z \cdot n \) is the total electron density. Ignoring small differences in the relativistic corrections, when the two energy losses are summed,

\[
\left( \frac{dE}{d\xi} \right)_{\text{Total}} = \left( \frac{dE}{d\xi} \right)_{ie} + \left( \frac{dE}{d\xi} \right)_{\text{Plasma}}
\]

\[
= -\frac{4\pi r_0^2 m_e c^2 Z P(E)}{\beta^2 A m_n} \left[ Z \ln \left( \sqrt{\gamma - 1} \gamma \beta m_e c^2 \right) - Z_B \ln \bar{T} - \chi_e \ln (\bar{\hbar}\omega_p) \right],
\]

(3)

where \( P(E) \) is the relativistic correction. There is an ionization fraction dependence due to the inequality between \( \ln \bar{T} \) and \( \ln (\bar{\hbar}\omega_p) \). An ionized medium is more efficient at slowing positrons than is a neutral medium. The ionization fraction must be known as a function
of mass, radius, and time to determine the energy deposition exactly, but is not currently well understood. Pinto & Eastman (1996), Liu, Jeffery & Schultz (1997), and Fransson & Houck (1996) arrived at different ionization structures for similar models. Unable to improve this situation, we choose to calculate a range of ionization fractions to bracket the possibilities. We consider extreme values of the ionization fraction, 0.01 and 3.0, because the actual values are almost certainly between these during the times we consider.

The positron transport was done with a 1D Monte Carlo code. SN models were reduced to 75-150 zones and up to 34 elements. Positrons were emitted at equally spaced time intervals from each zone (volume-weighted, random locations within the zone), weighted according to the $^{56}\text{Ni}(\text{zone},t)$. Positrons were followed in steps of equal column depth; the time, energy, radial distance, zone, pitch angle, and annihilation probability were re-evaluated at each step.

The range of positrons in various solid media has been measured in the laboratory (ICRU Report #37 (1984)). Figure 3 compares the laboratory results with the ranges of individual positrons through SN ejecta, combining the data from a number of models. The model results for low ionization are in good agreement with the laboratory results, whereas the higher ionization leads to the medium being 2-3 times more efficient at stopping positrons. The spread of ranges for the triply ionized ejecta reflects the variation of the ejecta’s composition. A positron will have a longer range in triply ionized iron than in triply ionized carbon because of the $\chi_{A}^{e}$ dependence of the more efficient energy loss to the plasma. It is unlikely that the zones rich in C, O, Si and the other intermediate elements will maintain as high a level of ionization as the Fe zones (where the decays occur), so the uniformly triply-ionized approximation is a lower limit for positron escape. The 1% ionized ranges have less scatter because the ionization-excitation range depends upon $Z_{A}^{e}$, and with $Z_{B} \approx Z$, $Z_{A}^{e} \approx 0.5$ in both Fe-rich zones and C-rich zones.
The range determines the escape fraction because when the column depth to the
surface at a given radius is less than the stopping power for a given emission energy, a
positron of that energy can escape (after it deposits a fraction of its energy in the ejecta). A
number of groups have transported positrons with the same treatment used with photons,
assigning a $\kappa_{e^+}$, an “effective positron opacity”, incorrectly giving them an exponential
distribution of ranges. We do not use $\kappa_{e^+}$, but we can estimate its value for comparison
from our results. Defining that $\kappa_{e^+} \equiv$ the mean of the inverse of the range expressed in
units of inverse column depth (cm$^2$ g$^{-1}$); for $\chi_e = 0.01$, $\kappa_{e^+} = 4$; while for $\chi_e = 3$, $\kappa_{e^+} =$
14. Colgate transported positrons with $\kappa_{e^+} = 10$ cm$^2$ g$^{-1}$, as did Ruiz-Lapuente. Axelrod
argued for $\kappa_{e^+} = 7$ cm$^2$ g$^{-1}$, which was the nominal value in most fits shown by CAPP.

2.3. Magnetic Field Considerations

The efficiency of matter at slowing positrons is one factor in determining the positron
escape, the quantity of matter traversed enroute to the surface is another. The effects of the
total mass and the nickel distribution will be discussed in section 4, but these are secondary
to the effects of the magnetic field (CL), which will force positrons to follow curved paths.
The progenitor white dwarfs have been observed to have initial field strengths of $10^5$ -$10^9$
Gauss (Leibundgut 1995). The field is assumed to diffuse on a long time-scale relative
to the positron lifetimes, so the flux is treated as frozen-in. Thus the expansion causes
the field strength to evolve according to the relation, $B(r) = B(r_o) r_o^2 r^{-2}$. If the resulting
field is strong enough to make the positron gyroradius smaller than the ejecta at a given
time, the geometry of the field must be considered. Little is known about SN Ia magnetic
fields, so we consider three scenarios; radial magnetic field, disordered field, no field. Thus
we also bracket the extreme magnetic field configurations, and late observations of SN Ia
luminosities are potentially probes of the field characteristics.
A radial field is an approximation of the effect of the rapid, homologous expansion of the ejecta stretching out the arbitrarily oriented field lines as it changes scale by a factor $10^7$ as it grows. Positrons spiral inward or outward on these field lines, changing pitch angle due to mirroring and beaming, as described by CL. These bend trajectories radially outward, so this “radial scenario” is a favorable one for positron escape.

A turbulent, confining field is presumably adjusted or generated by expansion dynamics (RL & Spruit 1997), with the limiting case of a positron having no net radial motion (in mass coordinates) as it meanders near the location of its emission zone for all times. This is called the “trapping scenario”. There is some survival of positrons in place, if their slowing times exceed the age of the supernova, but by definition there is no escape.

The third scenario ignores magnetic fields, so the positrons travel straight-line trajectories. This is referred to as the “free scenario”.

3. Bolometric Light Curves

Combining the results of the gamma-ray and positron transport calculations, we obtain the rate of energy deposition throughout the SN ejecta. This energy is then mainly contained in suprathermal free electrons that slow and recombine into atoms, which then deexcite. As discussed for positrons above, once the electrons reach energies of a few keV their slowing times, and the duration of the subsequent processes are short. At late times all the optical photons generated escape immediately without interaction. So, for the time of interest here, the major difference between the decay rate of the radioactivity and the supernova (optical) luminosity is the propagation times of the gamma rays and positrons, and we therefore treat the calculated power deposited and bolometric luminosity as being interchangeable. A typical calculated bolometric light curve (power deposition) is shown in
3.1. Time Evolution

The initial climb to peak luminosity is generated by energy deposition from the thermonuclear burning and from the $^{56}$Ni decays, followed by the diffusion of light to the photosphere. The width of the peak is governed by the diffusion time from the $^{56}$Ni to the photosphere. Observed SNe have shown variations of peak width, which should arise naturally out of any successful models. The factors that determine the light curve peak width are currently debated. Höflich (Höflich & Khokhlov 1996) asserts that the ejecta mass, the $^{56}$Ni distribution, and the $^{56}$Ni mass all influence the peak width. He fits narrow peaks with models which underproduce $^{56}$Ni (relative to W7). Pinto & Eastman (1996) asserts that the peak width only depends upon the first two. Their radiation transport calculation showed that the energy deposition from the $^{56}$Ni adjusted the structure of the ejecta to make the peak width independent of the $^{56}$Ni production. They explain narrow peaks with low-mass models.

Because we do not do the optical radiation transfer, we can not apply our calculations to this early epoch. We simply take models shown by other authors to fit individual supernova early light curves and spectra and calculate their subsequent bolometric light curves to be compared with late observations. By 60 days after the explosion, the photosphere has receded to the SN center; after this time our calculations should trace the bolometric light curve.

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4Unless otherwise stated, times quoted refer to time since explosion

5SN 1991bg may be the explosion of a 0.6 $M_\odot$ WD. If so, bolometric curves may fit the data as early as 30 days. The choice of 60$^d$ as the time to initiate light curve fitting follows
The light curve decline after $60^d$ is governed by the $^{56}$Co decay and the falling gamma-ray optical depth. Thus the light curve shape is a diagnostic of the mass overlying the Ni-rich zones and the velocity structure. The decline of the gamma deposition fraction ($f_\gamma$) makes the light curve steeper than the decay. Faster models reach the transition to positron dominated power, when $f_\gamma = 0.03$, earlier. The time of this transition varies among models, occurring at $130^d - 520^d$. The ejecta is still too dense at these times for the positrons to have appreciable lifetimes, so the light curves flatten toward the $^{56}$Co decay line (RLS). During this epoch, the various field geometry scenarios produce identical results. Further expansion of the ejecta leads to appreciable positron lifetimes, and in the radial and free scenarios, escape. Then the light curves begin to separate. For the radial and free scenarios, positron escape leads to kinetic energy loss from the system and a drop in the light curve. For the trapping scenario, a finite positron lifetime combined with the exponential decline in the number of newly created positrons leads to a shallow dip followed by a late flattening of the light curve, as positron kinetic energy is stored and delivered a (lengthening) positron slowing time after emission. Figure 5 contrasts the integrated luminosities for the trapping and radial scenarios as compared to the instantaneous deposition approximation. The delayed luminosity is seen in figure 4 as the trapping curve is brighter than the instantaneous deposition curve at late-times. For the radial scenario, positrons (and thus kinetic energy) can leave the system, leading to a much larger deviation from the instantaneous deposition. As this energy is increasingly leaving the system at late-times, the radial light curve in figure 4 is dimmer than either the instantaneous deposition curve or the trapping curve. As the radial and trapping curves diverge, the separation becomes great enough to be measurable, in principle.

from Leibundgut & Pinto 1992.
3.2. Radial Magnetic Field vs No Field

It turns out that there is surprisingly little difference in the mean path traversed to the surface for these two cases. Assuming isotropic emission of positrons, the mean distance to the surface from a given point, for positrons not near the center of the ejecta, is substantially larger than the radial distance to the surface because of the large solid angle perpendicular to the radius. In the radial field case, mirroring and beaming turn positron trajectories outward, but the extra path due to the spiral around the field adds similar distance as in the no-field case. The net energy deposition and positron escape for the models we consider are almost indistinguishable for these two cases. This result was anticipated by Colgate (1996), and can be approximately demonstrated analytically. We display radial field calculations, but remind the reader that for our spherically symmetric models the conclusions apply equally to field-free scenarios. For a few of the models, there were slight deviations at late-times ($t \geq 800\,d$, the field-free curves remaining steeper than the radial curves). We show field-free light curves only when the separation between these two cases is potentially detectable.

3.3. Energy Deposition at Very Late Times ($1000\,d$)

The effects of positron escape on the SN light curve are moderated somewhat by gamma-ray energy deposition. Longer-lived radioactivities that were overwhelmed at earlier epochs become important at late times. Two such radionuclides are $^{57}\text{Ni}$ and $^{44}\text{Ti}$. The decay of $^{57}\text{Ni}$ proceeds with $\tau_{\text{Ni57}} = 52^h$ and $\tau_{\text{Co57}} = 392^d$, thus at $500^d$, 28% of the $^{57}\text{Co}$ has yet to decay. The $^{57}\text{Co}$ decay energy is only 1/10 that of the $^{56}\text{Co}$. For W7 the energy available from $^{57}\text{Co}$ equals that available from $^{56}\text{Co}$ at $1000^d$. Other models have similar $^{57}\text{Ni}/^{56}\text{Ni}$ ratios. $^{44}\text{Ti}$ is an even longer-liver radionuclide, with a mean-life recently estimated to be $85^y \pm 1^y$ (Ahmad et al. 1997). The 1.3 MeV decay energy is substantial, but the slow decay
rate delays the cross-over to $^{44}$Ti dominated deposition until 2500$^d$, when no SN Ia has been detected. Five models had the $^{57}$Co and $^{44}$Ti masses included. For the other models, $M_{C057} = 0.041 M_{C056}$ and $M_{Ti44} = 1.5 \times 10^{-5} M_{C056}$, to match W7. Figure 6 shows the fraction of the luminosity that is due to the deposition of positron KE. The positron deposition is dominant from 300$^d$ -800$^d$ for the radial field geometry. The effects of including longer-lived radioactivities is shown by the splitting of the curves at late times.

3.4. Additional Potential Sources and Effects

There are a number of other potential sources of luminosity, both intrinsic and extrinsic. One extrinsic source is the “light echo”, bright peak light scattered by dust back into the line of sight after light travel delays. SN 1991T was dominated by a light echo by day 600 (Schmidt et al. 1994), as discussed in section 4. Another extrinsic source is the interaction of the ejecta with the surrounding medium. This interaction will eventually be important, but should be identified by distinctive spectral and temporal characteristics.

The SN model light curves presented in this work are based on the assumption that the deposited power is instantly radiated in the UVOIR bands, during the time 1–2 years. Furthermore, during this epoch, we usually have only the V and/or B band observations, instead of the bolometric luminosity, with which to compare models. Fitting model light curves to single or dual bands is susceptible to intrinsic spectral evolution effects. As the secondary electrons’ lifetimes increase and the collisional de-excitation rates fall, a delay develops between the positron energy deposition and emission of UVOIR light, an effect called “freeze-out” by Fransson (1996). If the Fe I and II states form in abundance without photoionization or charge exchange destruction, then $[\text{FeII}]\lambda 25.99 \mu \text{m}$, $\lambda 35.35 \mu \text{m}$, and $[\text{FeI}]\lambda 24.05 \mu \text{m}$ fine structure emission lines are produced. These lines are beyond the UBVRI bands and are undetected. This effect is referred to as an infrared catastrophe (IRC) by
Axelrod (1980). Both freeze-out and IRC phenomena must be considered and are discussed in section 5. It is clear that at very late times, many complicating effects, including new sources of luminosity and sinks outside the normally observed bands can be important. Therefore we confine our conclusions to the times when $^{56}$Co decay dominates the power input and the B and V bands track well the bolometric luminosity.

3.5. SN Models

We considered twenty-one models, which span the range of ejecta mass, $^{56}$Ni mass, and kinetic energy. One deflagration (W7) (Nomoto, Thielemann & Yokoi 1984), a normally luminous helium detonation (HED8) (HK96), two subluminous helium detonations (WD065, HED6) (Ruiz-Lapuente et al. 1993; HK96), two superluminous helium detonations (HECD, HED9) (Kumagai 1997; HK96), one accretion-induced collapse (ONeMg) (Nomoto 1996), eight delayed or late detonations (DD4, M36, M35, M39, DD2O2C, DD23c, W7DN, W7DT) (Woosley 1991; Höflich 1995; Höflich, Wheeler & Thielemann 1998; Yamaoka 1992), three pulsed, delayed detonations (PDD3, PDD54, PDD1b) (Höflich, Khokhlov & Wheeler 1995), and two mergers (DET2, DET2ENV6) were included. Their characteristics are shown in Table 1.

In figure 7 we show the luminosity due only to the gamma deposition. As expected, the total luminosity roughly traces the amount of $^{56}$Ni produced. The steepness of the early decline measures the mass overlying the Ni. The models then flatten, with slopes becoming nearly equal. In figure 8 we add the positron contribution to create bolometric light curves for radial field geometries, assuming 1% ionization. The curves start at and are normalized to 60$^d$ to show the evolution of their shape from 60$^d$ -400$^d$. There are often many observations during this epoch, so the different shapes provide a test of whether the model (regardless of field characteristics) fits the light curve. One interesting
feature is the steepness of the Chandrasekhar mass models, in which the $^{56}\text{Ni}$ is covered by a large overlying mass. We interpret this steepness to be due to the delayed onset of the positron-dominated epoch. The low mass models enter this epoch earlier, so they flatten toward the decay line. Table 1 shows the day when gamma deposition falls to equal the positron deposition. HED6, WD065, ONeMg, DET2 have relatively little mass and transition before $180^d$; PDD1b and DET2ENV6 have much more overlying mass and transition at $300^d$ or later. PDD1b thins to gamma photons so slowly, that it remains as bright as the low mass models due primarily to gamma deposition. Other than the extreme model PDD1b, shallow declines after $60^d$ suggest models with less mass overlying the $^{56}\text{Ni}$, steep declines suggest more overlying mass. This trend is also evident in the light curves calculated by RLS, who parametrize the slope at various epochs in their Table 3. The separation of WD065 and ONeMg from HED6 after $200^d$ is due to the earlier survival of positrons in WD065 and ONeMg.

Figure 9 is an extension of figure 8 to $1000^d$, but including the curves from positron trapping scenarios. This epoch emphasizes the differences in positron transport between the field geometries. The most noticeable feature is that the radial models are approximately equivalent and steep, whereas the trapping models flatten according to the percentage of $^{56}\text{Ni}$ produced in the outer portions of the SN. RLS mention that the late light curves of trapping field scenarios flatten relative to instantaneous deposition, but state that the effect is small. Our results show the effect to be large. Thus, the $400^d$ - $800^d$, positron-dominated epoch is a diagnostic of field characteristics, not of model types. Also apparent in this figure is that the “massive” models show separation between the field scenarios much later and to a lesser degree than the rest of the models. Massive in this sense refers to a large mass of slow ejecta overlying the $^{56}\text{Ni}$-rich zones.

The variety of shapes at early epochs and then the dramatic separation between the
predictions of positron trapping in a turbulent field geometry and positron escape in a radial or weak field show that $60^d$ and later bolometric light curves yield a wealth of information as to the structure and dynamics of the SN ejecta.

4. Comparison With Observed Light Curves

Ideally, to probe the SN structure using light curves, model-generated bolometric light curves are compared with observed bolometric light curves. Observed bolometric light curve reconstructions, to date, are at best based on measurements in the U,B,V,R,I bands, with some information from the J,H and K bands. As the SN dims, the photometric uncertainties increase and for many light curves, the number of bands observed decreases, leading to less accurate bolometric reconstructions. We use the available bolometric light curves: SN 1992A to day 420 (Suntzeff 1996), SN 1991bg to day 220 (Turratto et al. 1996), SN 1972E to day 420 (Axelrod 1980) \(^6\), SN 1989B to day 135, and SN 1991T to day 108 (Suntzeff 1996). The best epoch to observe positron transport effects is during the $500^d$ - $900^d$ range; only SN 92A and SN 72E extend close to that epoch. Nonetheless, the SN 91bg, SN 89B and SN 91T light curves are valuable in checking the fit of a specific model during the gamma-dominated phase. For each model we consider for a particular event, we simply fit the calculated light curve to the “observed” bolometric light curve. Thus we avoid the uncertainties in distance, extinction, and bolometric correction. We then show the later, positron-dominated light curves relative to this fit for comparison to the more limited data in one or a few bands. RLS fit models to the bolometric luminosities of SN 1991bg and SN 1992A, Mazzali et al. (1996) fit SN 1991bg. In sections 5.1 5.2 and 5.4 we

\(^6\)We do not use the 720 day data point because we consider the extrapolation of an entire bolometric light curve from a 1200Å wide spectrum to be too uncertain
will discuss our results in relation to theirs.

When there is insufficient data to reconstruct bolometric light curves we compare model bolometric shapes to individual band photometry. This assumes that at late epochs there is little color evolution. We must be able to rule out any increasing shift of the luminosity into unobserved bands. Lira (1998) showed that the collective tendency is for the color indices stop evolving after day $100-120^d$. In figure 10 we show the U, B, V, R, and I band variations of six of the SNe used in this study. B-V peaks around $t \approx 30-40^d$, then decreases to approximately zero near day 100 (except SN 1991bg). At the (B-V) peak, the V band contains most of the energy and then declines to $B-V \approx 0$ with the B band a potentially important contributor. The V band is the best single band to trace the supernova bolometric light curve. The five bolometric light curves permit us to estimate the error introduced by fitting with only the V band. As shown in figure 11, the inaccuracies in using the V or B band data for the bolometric luminosity are $\leq 0.2^m$ during the $60^d-120^d$ epoch. The similar procedure in comparing model-generated bolometric light curves to band photometry was also employed by CAPP who used V band data for every epoch.

Theoretical arguments about color evolution have been made by Axelrod and Colgate (1996), who disagree as to whether collisional or radiative processes dominate the emission from the recombination cascade. The competition between collisional and radiative processes hinges upon three factors: level of ionization (temperature in the collisional scenario), density, and atomic cross sections. Fransson & Houck (1996) addressed these issues, calculating multi-band model light curves. The technique worked well for the type II SN 1987A, but the type Ia light curves generated from the model DD4 showed a sharp decrease in U,B,V,R,I around day 500 due to the infrared catastrophe (IRC), and were inconsistent with SN 1972E. Why the IRC does not apparently occur in SN Ia is something of a puzzle. The model DD3 contains more $^{56}$Ni ($0.93 \, M_\odot$ versus $0.62 \, M_\odot$ for DD4) and
thus maintains a higher level of ionization. This delayed the onset of the IRC, but still could not fit the observed light curves of SN 72E. It is important for our discussion that any onset of the IRC is abrupt; this does not lead to a gentle decline of the light curve as we find for positron escape. Fransson & Houck (1996) also considered clumping in the ejecta. It might delay the onset of the IRC for the inter-clump regions, but it hastens its onset in the clumps. It remains to be seen if spectra modeled with clumping will reproduce the observed spectra.

The atomic cross sections provide a third explanation for the lack of color evolution. If the radiative transition probabilities are underestimated, the radiative scenario might dominate. Fransson & Houck increased the recombination rates by a factor of 3 to model the spectra; perhaps additional adjustments are required. Few of the SNe observed at late epochs show convincing color evolution. Two of the three SNe that continue to evolve after $120^d$, 1986G and 1994D, seem to settle into constant color indices later. All the evidence suggests to us that the V (and probably B) band tracks the bolometric luminosity of SN Ia at late times. We emphasize the SNe for which there are at least two measured bands for most of the observed light curve.

5. Comparison of Models to Individual SNe

The amount, type, and quality of data varies among SNe. A summary of the observations used in this study are listed in table 2. A wider range of model fits to SNe is shown in Milne (1998). We primarily consider SN Ia models shown by others to describe well the early light curves and/or spectra of particular well-observed events, calculating their light curves to late times. Models are considered for a given event if they can reproduce some combination of the following features: distance-dependent peak luminosity estimates, rise-time to peak luminosity and peak width, early spectral features and light
curve shapes for multiple color bands. Generally the early data available do not uniquely define the model parameters, or even the basic type of model. For some cases, the suggested models are quite different. An example of this is SN 1991bg, which is fit with two low-mass models (an 0.6 M⊙ AIC and a 0.65 M⊙ HeDET), a 1.4 M⊙ pulsed model and a 1.4 M⊙ deflagration model. Our first test is whether a model can fit the earlier nebular light curve, which probes the transition from gamma to positron domination. We then examine whether models that pass this first test can determine the magnetic field configuration and degree of ionization. Thus, this study is able to add another constraint to the SN fitting puzzle, as well as determining if positrons escape from SN ejecta.

5.1. SN 1992A in NGC 1380

SN 1992A occurred in the S0 galaxy NGC 1380 and was observed extensively. It is often held up as an example of a normal SN Ia. Extinction appears to be minimal, making SN 1992A an excellent candidate for photometric analysis. SN 1992A is one of three SNe treated in both RLS and CAPP. We show the fits of three models to SN 1992A: DD23C, M39 and HED8. DD23C was fit on the recommendation of Peter Hőflich (1998), and also because Kirshner et al. (1992) fit the spectral data with a modified version of DD4, which is similar to DD23C. RLS combined the distance estimates to NGC 1380 with Suntzeff’s UVOIR bolometric estimation to suggest that the peak bolometric luminosity was between 42.65 and 43.00 dex. This suggests that a sub-luminous model might be required.\footnote{A recent study by Suntzeff et al. 1998 suggests that NGC 1365 (treated to represent the center of the Fornax cluster) may be a foreground galaxy in the cluster. If this is the case, then SN 1992A may be only mildly sub-luminous, and at a distance in agreement with Branch et al. 1997.} M39
is a delayed detonation that has a peak bolometric luminosity of 43.06. We choose it as a compromise between the delayed detonation scenario suggested by the spectra, and the low luminosity suggested by distance estimates. CAPP listed the distance to NGC 1380 as 16.9 Mpc, with E(B-V) = 0.00 m, and fit the data with a 1.0 M⊙ model which produced 0.4 M⊙ of 56Ni. We instead use the similar model HED8.

Figure 12 shows the fits of DD23C and HED8 to the bolometric light curves of SN 1992A. For this object the bolometric light curves are reconstructed to late enough times that we can use them directly to study positron energy input. Assuming a 0.025 dex uncertainty for each data point, DD23C provided the best fit, varying only the overall amplitude, of the suggested models in the 55–420d epoch, fitting with 81% confidence for the radial curve. The trapping version of that model was rejected at the 99.91% confidence even when renormalized. The numerical results are shown in table 3 for 1% ionization, triple ionization with a radial field geometry, and for 1% ionization with a trapping field. The low mass model, HED8 did not fit above the 10−4 level for any scenario. RLS also fit a 0.96 M⊙ model to SN 1992A. Our results are consistent with theirs in that the models are brighter than the data after 100 days. The CAPP fit for 7 ≤ κe+ ≤ 10 remained too bright from 20d–320d, also in agreement with our results. The best fitting class of models were the delayed detonation models; W7, DET2ENV6 and PDD54 were the only models other than delayed detonation models to fit at better than the 20% confidence level.

We show the fits of two models to the V data, DD23C and M39, in figure 13. Both models follow the falling luminosity better with positron escape than with trapping. Fitting time-invariant ionization scenarios to the V data with the published uncertainties, none of the models provided a fit better than χ²/DOF=18. The numerical fits to the V band

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8We note that the B-V color of M39 is too red to fit 92A according to the model generated light curves of Höflich, even with zero extinction.
data (table 2) show that with the scatter in excess of the stated uncertainties, none of the models provide statistically acceptable fits. In absolute terms, our goodness-of-fit statistics are questionable, but the fits are better for radial scenarios for almost every model.9

The other delayed detonation models yielded fits similar to DD23C and M39 for the V data, demonstrating that the observation of positron escape at late times is not strongly model-dependent. The 928d point might herald the onset of another source of power. Possibilities include other radioactivity, such as 22Na or 44Ti (but not 57Co, which is too weak), recombination energy lagging earlier, higher ionization input (Clayton et al. 1992, Fransson & Kozma 1993), and positrons encountering circumstellar material, as well as others. In summary for SN 1992A: delayed detonations are the most promising model types, all of which overproduce the late light V light curves without escape of positrons.

5.2. SN 1991bg in NGC 4374

SN 1991bg occurred in the galaxy NGC 4374 and is the best observed member of a class of sub-luminous SNe that have a fast decline from peak luminosity. SN 1991bg appeared to be very red at peak suggesting either significant extinction (∼0.7m), an intrinsically red SN, or both. The fact that SN 1991bg and SN 1986G continued to show color evolution after 120d suggests that they were intrinsically different than normal SN Ia. We fit SN 1991bg with three models that have been suggested to explain this SN; WD065, PDD54 and ONeMg, as well as a fourth model, W7. The models WD065 (a helium detonation) and ONeMg (an accretion induced collapse) decline faster from peak luminosity relative to 1.4 M⊙ models because they have less overlying mass (but similar velocity structures) leading

9The model DET2ENV6 fits the late V band data well (but less so the bolometric data) and may warrant further investigation.
to a lower optical thickness. Ruiz-Lapuente (1993) fit WD065 to the maximum and nebular spectra, and later (RLS) to the bolometric light curve. PDD5 is a pulsed delayed-detonation model that produces very little $^{56}\text{Ni}$, and maintains a lower level of ionization (relative to W7 and normally luminous models) which decreases the free-free opacity and thus the overall opacity. Höflich (1996) fit PDD5 to B,V,R, and I band data out to 75$^d$, suggesting the distance to NGC 4374 to be $18 \pm 5 \text{ Mpc}$ with E(B-V)=$0.25^m$. PDD5 is unavailable, so we use the similar PDD54. W7 was included because it provides the best fit of all models, it has not been suggested by other authors. The fits for the four models to the bolometric data are shown in figure 14; fits to the V data is shown in figures 15 and 16. Present in the B and V data is a disagreement after 140$^d$ between the data taken by Leibundgut et al. (1993) and that taken by Turatto (1996), the Turatto data suggesting the SN was fainter.$^{10}$

The bolometric light curve was calculated by Turatto et al. (1996) from the photometric data, and strongly relied upon the B and V bands. No models were able to reproduce the steep decline of the Turatto data. Placing 0.04 dex error bars on the bolometric data after 50$^d$ and ignoring the data after 140$^d$, PDD54 provided the best overall fit at the 27% level. WD065b fit below the 2% level, ONeMg below $10^{-5}$. Every model remains too bright to fit the bolometric data out to 250$^d$, with no model fitting above the 1% level.

The B and V band data shows the models WD065 and ONeMg to be bright from 140$^d$–250$^d$, too bright to fit either set of data. PDD54 and W7 were able to fit the Leibundgut data within the uncertainties. RLS fit WD065 to the bolometric data, invoking the weak-field scenario. For our calculated WD065 light curve, the weak-field scenario was fainter than the radial scenario, but the light curve remained too bright to fit the data. The dashed line shows the prediction for 100% transparency to positrons (zero deposition

$^{10}$The third data set of Filippenko tends to confirm the measurements of Turatto, but do not extend beyond 140$^d$. 
of positron kinetic energy). This line fits the data, but there is no physical justification for this extreme scenario. Our results agree with the results of CAPP, who tried to fit a 0.7$M_\odot$ model that produced 0.1$M_\odot$ of $^{56}$Ni and determined that only zero positron deposition ($\kappa_{e^+}=0$ in their terminology) would approximate the data. For ONeMg, the slope of our bolometric light curve agrees with Nomoto et al. (1996) from 60$^d$–90$^d$. It is the 120$^d$–450$^d$ epoch that excludes ONeMg as an acceptable model. Mazzali et al. (1996) tried to reproduce the spectra of SN 1991bg with a 0.62 $M_\odot$ version of W7, and as a by-product generated a bolometric light curve out to 220$^d$ post-explosion. Their light curve assumed positron trapping and was too bright to fit the data after 110$^d$. They argued that this epoch is too early to expect positron escape and suggested that there is unseen emission leading to an erroneously low bolometric light curve. Our light curves for the low-mass models WD065b and ONeMg have the same characteristics as theirs, and positron escape is insufficient to explain the low luminosity in the 110$^d$–220$^d$ epoch.

The inability to fit any model to the Turatto data tempted us to favor the trend emerging from the Leibundgut data over the Turatto data. But, the light curve from SN 1992K forbids that action. SN 1992K has near peak spectral and photometric properties similar to SN 1991bg, and the B and V data follows a SN 1991bg-like shape. The V data extends out to $\sim$155$^d$. The existence of a second example of this steep decline forces us to conclude that there exists a sub-class of type Ia SNe for which we are unable to fit the light curves with the models in our possession without invoking a larger extinction than suggested. The flatness of low mass models during the positron-dominated phase suggests that that class of models possess the opposite tendency from that required. The solution to this problem remains unclear.
5.3. SN 1990N in NGC 4639

SN 1990N was unusual in that Co lines were detected earlier than existing models predicted and the intermediate mass elements had higher velocities (Leibundgut 1991). The near-maximum and post-maximum spectra were normal, suggesting normal models such as W7 could explain them. The late detonation model, W7DN, was created to fit the early spectra and transition to W7. This was accomplished by having a deflagration accelerate into a detonation at $M_r=1.20M_\odot$. Yamaoka (1992) discussed how the extra $^{56}\text{Ni}$ modifies the rise to peak light to fit SN 1990N. Höflich (1996) fit DET2ENV2/4 and PDD3 to the multi-band photometry of SN 1990N, for a distance to NGC 4639 of $20\pm5$ Mpc. The multi-band coverage is very good, but a bolometric light curve has not been published. There was an unfortunate gap in the light curve from $70^d$–$200^d$, as the SN was too close to the Sun for observations, hampering our ability to differentiate among model types.

Figure 17 shows the models W7DN and PDD3 fit to the B and V data. Both models fit the $190^d$–$300^d$ data well and then show a steepening consistent with positron escape. The normally luminous DD and PDD models provided similar fits, with all models giving worse fits for positron trapping.

5.4. SN 1972E in NGC 5253

SN 1972E was not observed pre-maximum and thus the models are not well constrained. We assume the explosion date to be JD2441420 (Axelrod 1980). The photometry out to $+169^d$ is photoelectric, with later photometry derived from spectra (Kirshner & Oke 1975). The bolometric light curve published by Axelrod was also generated by a model fit to the Kirshner spectra. We fit three models to 72E: W7, M35 and HED8. RLS fit W7 to the bolometric data, invoking a transition from turbulent confinement (with $B_o=10^5$ G) to
weak-field trajectories around 500$^d$. Their W7 light curve fit well before 500$^d$. The transition was discussed conceptually by RLS, but not modelled. Höflich (1996) fit the model M35 to the multi-band photometry of 72E, suggesting the distance NGC 5253 to be 4.0 ± 0.6 Mpc. The model HED8 is shown because of the agreement with the bolometric light curve. All three models are consistent with the $^{56}$Ni mass suggested by the nebular spectra, 0.5–0.6M$_{\odot}$ (Ruiz-Lapuente & Lucy 1992). Colgate (1996) suggests a 0.4 M$_{\odot}$ model to explain 72E, this possibility was not investigated due to the lack of a suitable model.

Figure 18 shows the fits of HED8, W7, and M35 to the B, V and bolometric data. None of these models can be rejected, but all fit better with the radial field scenario and significant positron escape. None of the models fit the 700$^+$ data point, with all remaining too bright.

5.5. SN 1991T in NGC 4527

SN 1991T was unusual in the width of the luminosity peak and in the absence of SiII and CaII absorption lines (Filippenko et al. 1997). It is the prototype of superluminous type Ia SNe. It was also an example of a SN whose late emission was overwhelmed by a light echo, as shown by Schmidt et al. (1994). Suntzeff (1996) derived a bolometric light curve to 87$^d$ post-B maximum against which we tested models. There was also a gap in observations as the sun was too near the SN. We show the fits of two models to SN 1991T, the late-detonation W7DT, and the superluminous helium detonation HECD. The model W7DT was proposed by Yamaoka et al. (1992) to explain the lack of intermediate mass elements in the pre-maximum spectra, followed by a normal spectrum post-maximum. Nomoto et al. (1996) modelled the bolometric light curve for W7DT and scaled it to fit the V data. Höflich (1996) suggested PDD3 and DET2ENV2 based upon fits to multi-band photometry, suggesting the distance to NGC 4527 to be 12 ± 2 Mpc. Liu et al. (1997)
argued that the superluminous 1.1 M⊙ helium detonation, SC1.1 (which produces 0.8 M⊙ of 56Ni), fit the nebular spectrum (301d) better than did the models W7, DD4 and SC0.9. To fit SN 1991T, Liu et al. (1997) assumed a distance of 12–14 Mpc and E(B-V)=0.0 m–0.1 m. We approximate SC1.1 with HECD, a 1.06 M⊙ helium detonation that produces 0.72 M⊙ of 56Ni. Pinto & Eastmann (1996) fit DD4 (with pop. II elements added) to the B and V data for SN 1991T out to 60 d, suggesting a distance of 14 Mpc for E(B-V)=0.1 m.

RLF estimated the 56Ni production to be 0.7–0.8 M⊙ of 56Ni using nebular spectra; Bowers’ (1997) 56Ni production (when adjusted as explained in section 4) is 0.7±0.2 M⊙. W7DT and HECD are both consistent with this, while PDD3 slightly underproduces 56Ni.

Figure 19 shows the fits of W7DT and HECD to the V data. The late V data was fit by adding a constant light echo component. Both models show that the radial field scenario with positron escape provides better fits. The dashed lines show the radial light curves without an echo, the dot-dashed lines show the trapping light curves without an echo. The trapping curves remain too bright during the 200 d–500 d epoch even with no contribution from a light echo, arguing strongly against trapping. The 1.1 M⊙ and 1.4 M⊙ models have similar late light curves, suggesting that they can not resolve the ambiguity between Chandrasekhar and sub-Chandrasekhar mass models for superluminous SNe. The fact that the radial curve explains the data with no echo contribution until 470 d perhaps suggests that the light echo that “turned on” after 450 d, an effect that could be explained by the SN light sweeping through a dust cloud. The asymmetry of the image of the SN 1991T light echo would be consistent with reflection off of discrete cloud(s) (Boffi et al. 1998). Unfortunately, the light echo interrupted the positron dominated epoch before the optimal time to observe positron escape (∼600 d). Whereas it may be possible to eventually account for and subtract out the contributions from a light echo, we do not fit light curves into the light echo phase other than to demonstrate the phenomenon.
SN 1993L was observed by CAPP and fit by the same model used for SN 1992A. The strength of the SN 1993L data is the continuous multi-band photometry extending to beyond 500\textsuperscript{d}. The data were published without uncertainties. There are no published spectra, so the best model was selected entirely by the fit to the B and V data. An additional complication is that the SN was discovered after maximum, which eliminated that discriminant. CAPP assumed the explosion date to be JD 2449098, the distance to be 20.1 Mpc and the extinction to be E(B-V)=0.75\textsuperscript{m}. With these assumptions, SN 1993L appears to be quite similar to SN 1992A. CAPP noted two differences between the two SNe; SN 1993L had a slower nebular velocity and a higher degree of V band curvature from 100\textsuperscript{d}–500\textsuperscript{d}. We note the additional difference that the SN 1993L light curve was dimmer from 25\textsuperscript{d}–55\textsuperscript{d} and again from 100\textsuperscript{d} to the cross-over at 400\textsuperscript{d}. Explaining these features is difficult, but we note that some of the PDD and DD models studied by H"oflich & Khokhlov show these features.

Assuming the photometry errors to range from 0.1\textsuperscript{m}—0.5\textsuperscript{m} from 60\textsuperscript{d}–550\textsuperscript{d}, only PDD1b was excluded at the 99\% confidence level, all other models and scenarios were consistent at the 30\% level or better. We show in figure 20 the fits of HED8 and DD4 to the B and V data. The radial curves for both models yielded similar fits within the scatter. For HED8, the trapping curve remains much too bright to fit the data. SN 1993L does not provide strong evidence of positron escape, but the radial light curves fit at least as well as trapping curves for any models tested.
5.7. SN 1937C in IC 4182

SN 1937C reached a peak B magnitude of $8.71^m$ and was detected on photographic plates for over 600$d$. Branch, Romanishin & Baron (1996) have argued that that its spectral features are those of normal SNe Ia, while Pierce & Jacoby (1995) argued that SN 1937C is similar to SN 1991T and thus superluminous. Höflich (HK96) suggests N32, W7 and DET2 as acceptable models, and a distance of $4.5 \pm 1$ Mpc. We use the data of Schaefer (1994), which is a re-analysis of photographic plates from many observers, principally Baade (1938) and Baade & Zwicky (1938). Pierce and Jacoby (1995) also re-analyzed photographic plates of SN 1937C obtaining a higher value for $B_{\text{max}}=8.94^m$.

Figure 21 shows the fits of DET2 and W7 to the B data of SN 1937C. The 1% ionization, radial-field light curves for DET2 and W7 fit the data well at all times, giving the best fits ($\chi^2$/dof=1.6) of any model (and any field scenario). The field free scenarios for DET2 and W7 are nearly identical to the radial field scenarios. The light curve for SN 1937C extends late enough with high-quality data to convincingly trace a shape after 400$d$ consistent with positron escape. We also suggest that models with masses lower than 1.4 $M_\odot$ and normally-luminous pulsed-delayed detonation models appear to fit better than do delayed detonation models. We note that the same conclusions are reached if the original Baade and Zwicky data is used, or the re-analyzed data of Pierce and Jacoby is used (Milne 1998).

5.8. SN 1989B in NGC 3627

SN 1989B occurred in NGC 3627 and had considerable extinction. An additional complication is its location in the spiral arm of the host galaxy, giving considerable background contamination. The bolometric light curve of Suntzeff (1996) shows SN 1989B
to be similar to SN 1992A, but remaining brighter than SN 1992A from 90 days onward. HK96 suggested the models M37 and M36 based upon fits to the multi-band photometry; we fit M36 to B, V and bolometric data for SN 1989B. The distance suggested by HK96 is 8.7±3 Mpc.

Figure 22 shows the fits of M36 and ONeMg light curves to the bolometric and V data from SN 1989B. The late bolometric and the later B and V band light curves remained too bright to be fit by M36. HK96 fit the model M37 to this same data, their V light curve remaining bright enough to fit the data. Our light curve for M36 is 0.5" dimmer than the HK96 estimate for M37 at 365^d. Höflich & Khokhlov cautioned against over-interpreting the latter portion of their light curve, but as none of the delayed detonations tested in this study approached the brightness of their M37 light curve, further investigations may be warranted. The only model able to reproduce the light curve beyond 300^d is the 0.6 M_☉ model, ONeMg. To date, there has been no suggestion that SN 1989B was substantially subluminous; in fact, it has been considered a relatively normal SN Ia. The possibility that SN 1989B was produced by a low-mass WD can be tested, especially when the distance estimate is improved. If this explanation is correct, this SN is the singular example of a light curve best fit with positron trapping. Another explanation is that the late light curve was affected by a light echo or another effect of the complicated background subtraction. There are two reasons to believe that a light echo may have been present. The 330^d spectrum showed more continuum emission at 6000Å than is typically seen in the nebular spectra of SNe Ia. In addition, there was strong Na-D absorption from the host galaxy, an indicator of foreground dust. If the dust were near enough to, or surrounding the SN, a light echo may have been produced. As good spectra exist, this question is also potentially solvable. The existence of two dramatically different explanations for the late light curve of SN 1989B means the subtle effect of positron escape can not be clearly seen or ruled out.
5.9. SN 1986G in NGC 5128

SN 1986G was well observed, but occurred in the dust lane of NGC 5128 and suffered from considerable extinction. SN 1986G had a narrow peak and slow $\lambda6355\text{Å}$ Si lines, suggesting that it was intermediate between normal SNe Ia and SN 1991bg. The B-V color index continued to evolve $120^d$ after the explosion, a feature also seen in SN 1991bg, but not observed in normal SN Ia.\(^{11}\) We fit the models W7, M39 and HED6 to SN 1986G. HK96 fit W7 to multi-band light curves to $80^d$ post-explosion, suggesting the distance to NGC 5128 to be $4.2\pm1.2$ Mpc. M39 was used because the $^{56}$Ni mass of M39 is in closer agreement with the RLF estimate of $0.38\pm0.03M_\odot$. HED6 represents moderately sub-luminous, low-mass models.

Figure 23 shows W7, M39 and HED6 with the SN 1986G B and V data. The Cristiani et al. (1992) data is shown without uncertainties. The B band is corrected for $1.1^m$ of estimated extinction. The model curves are normalized at $120^d$, when the B and V bands cross over. All three models roughly reproduce the shape of the V light curve from $60^d$–$100^d$. The B data is brighter than the V data after $120^d$ and can be fit by both W7 and M39. HED6 remains brighter than both W7 and M39, and provides a poorer fit to the data. Only the single point at $425^d$ is late enough to test the positron transport conditions. This observation is consistent with radial or no magnetic field and positron escape, but with a realistic uncertainty it might not rule out positron containment.

\(^{11}\)It is important to note that the B-V index appears to approach zero by the last observation, a reversal of the $100^d$–$320^d$ behavior.
SN 1994D in NGC 4526

SN 1994D occurred in NGC 4526 and was observed by three groups until June 1994 and by Cappellaro et al. thereafter. We fit M36 and HED8 for this object. The wealth of multi-band photometry and spectra at early epochs allowed Höflich (1996) to tightly constrain delayed detonation models and to conclude that M36 was the best, at distance $16.2 \pm 2$ Mpc. Liu et al. (1997,1998) found that SC0.9 (a 0.9$M_\odot$ model which produces 0.43$M_\odot$ of $^{56}$Ni) fits the 301$^d$ spectrum. We use the similar model HED8. CAPP fit the V band data of 94D with W7. As seen in figure 8, W7 and M36 are virtually indistinguishable, so we use M36. The B-V index continued to evolve after 120$^d$, necessitating the inclusion of both B and V bands.\footnote{As with SN 1986G, B-V approaches zero at late times.} Figure 24 shows the fits of M36 and HED8 to the SN 1994D B and V data. The 150$^d$–300$^d$ gap precludes our discrimination among model types. The scatter after 300$^d$ prevents examination of the positron escape. It seems the light curves can not rule out either delayed deflagrations or He-detonations.

5.11. Summary of Observations

Ten SNe were analyzed, including super- and subluminous events, reddened and unreddened SNe, old ones recorded on photographic plates and recent SNe recorded on CCDs. Of the ten, five show strong evidence of positron escape (92A, 37C, 91T, 72E, 90N), three others are also consistent with significant positron escape but somewhat ambiguous, (93L, 86G, 94D), and for two others it was not clear which model actually described the early light curve and should be tested for its positron transport later (91bg, 89B). Only SN 1989B suggests the possibility that a trapping field may provide a better fit, and there are complications with that interpretation. As a group, the supernova light curves fall more
quickly than models, which fit well at early times, extrapolated to later times with all the positron kinetic energy deposited in and radiated by the ejecta. This is consistent with the escape of a substantial fraction of the positrons emitted by $^{56}\text{Co}$ after one year.

Regarding even earlier times, for sub-luminous SNe the Chandrasekhar mass models fit the light curves better than low-mass models. For normally luminous SNe, there are not enough observations from $60^d$–$400^d$ to choose between the model masses. The superluminous SNe can apparently be fit equally well by high-mass He-detonation models and nickel-rich Chandrasekhar mass models.

6. Type Ia SN Contributions to the Galactic 511 keV Emission

Table 3 shows the positron survival fraction of type Ia SNe at $2000^d$ and the resulting positron yields for all the models treated in this study. The range of values reflects the extremes of ionization fractions. The lower values correspond to triple ionization, the higher values are for 1% ionization. The yields vary between the two extremes by roughly a factor of three. The observations suggest that 1% ionization typically fits better, so we will quote 2/3 of that yield as a conservative estimate for each model. For radial fields, the Chandrasekhar mass models have a lower survival fraction when compared with equally luminous sub-Chandrasekhar mass models, but the larger nickel mass partially compensates for that fact. As a result, for all but the “heavy ” models, the yields are not strongly dependent upon model mass. The radial scenarios have greatly enhanced positron escape yields compared to the trapping scenarios.

Positron escape is best observed best in light curves when its relative effect is large, between $400^d$ & $1000^d$, but the positron yield in absolute terms is determined earlier: 80% of the escaping positrons do so between $178^d$–$546^d$ for W7 (94$^d$–492$^d$ for HED8). It is
conceivable, but probably not common, that the trapping field could apply until, say, 500\(^4\), when the field magnitude decreased to the point that the Larmor radius reached the ejecta radius and the object would cross over to the field-free regime. The “release time” for a positron of a given energy is proportional to the initial field strength, which might vary over many orders of magnitude. For one object we might incorrectly infer the positron escape for this reason, but not likely for many.

The positrons that escape retain a significant fraction of their emitted energy, as shown by CL and in figure 25, which compares the emission spectrum (dashed line) to the escape spectrum (solid line). With energies near 400 keV, the positrons have a considerable lifetime in the ISM, giving diffuse galactic 511 keV emission. To estimate the rate of positron injection into the ISM, we assume a 2:2:1 ratio of normal:subluminous:superluminous SNe. Considering DD23C, PDD3, and HED8, a reasonable yield for normal SNe is 8 \( \times 10^{52} \) positrons. For subluminous SNe, PDD54, DET2ENV6 suggest a yield of 4 \( \times 10^{52} \) positrons. From W7DT, DD4, and HECD (suggested by 91T) we estimate a yield of 15 \( \times 10^{52} \) positrons. Employing the above ratio then gives a mean yield of 8 \( \times 10^{52} \) positrons per SN Ia.

This gives a flux \((4\pi D^2)^{-1} \cdot y \cdot \text{SNR} \cdot f_{e+\gamma}\), where D is the distance, y is the positron yield per SN event, and SNR is the SN Ia rate, and \(f_{e+\gamma}\) is the 511 keV photons emitted per positron. Taking D=8 kpc, y=8 \( \times 10^{52} \) e\(^+\) SN\(^{-1}\), SNR=0.0032 SN yr\(^{-1}\), and \(f_{Ps}=0.58\) photons e\(^+\)\(^{-1}\) (which corresponds to a positronium fraction of 0.95), the flux is 6.3 \( \times 10^{-4} \) photons cm\(^{-2}\) s\(^{-1}\). An estimate of the uncertainty in this flux can be obtained by inserting D=7.7 - 8.5 kpc, y=3 -10 e\(^+\) SN\(^{-1}\), SNR=0.003 -0.06 SN yr\(^{-1}\), and \(f_{xe^-}=-1=0.5\) -0.65 (corresponding to a positronium fraction of 1.0 -0.9) into the formula. The flux then

\(^{13}\)This value was obtained from Capellaro et al. (1997) and assumes H\(_0\)=65 km s\(^{-1}\) Mpc\(^{-1}\). Hamuy & Pinto (1998) suggest a slightly larger value, 0.0042 SN yr\(^{-1}\).
ranges from (1.2 -8.6) x 10^{-4} photons cm^{-2} s^{-1}. The flux is on the order of the Galactic bulge component of the 511 keV flux as measured by OSSE. Purcell (1997) estimated the bulge flux to be 3.5 x 10^{-4} photons cm^{-2} s^{-1} and the galactic plane flux to be 8.9 x 10^{-4} photons cm^{-2} s^{-1}. SMM, with a 130° FOV, (Share et al. 1988) measured the total flux from the general direction of the galactic center to be 2.4 x 10^{-3} photons cm^{-2} s^{-1}; the type Ia SN contribution could be one-fourth of that flux. A more exact treatment of the level of agreement between the 511 keV flux as mapped by OSSE and the spatial distribution of Ia SNe is the subject of a forthcoming paper (Milne 1999).

7. Summary

We calculate the \(\gamma\)-ray and the positron kinetic energy deposition to produce “UBVOIR” bolometric light curves for the time when the photon diffusion time \((t\geq60^d)\) is short for various models of type Ia SNe. In calculating positron kinetic energy deposition into the ejecta, we calculate it for particular extreme environments, they are: radial magnetic field, turbulence magnetic field, and field free geometries in a 1% and triple ionization medium throughout the evolution. The deposited energy rate is assumed to instantaneously appear as “UBVOIR” bolometric luminosity and is compared with several observed bolometric luminosity when they are available or with B and V bands observed luminosity. In this work, we analyzed ten late time type Ia supernova light curves by comparing the light curves with the calculated light curves. It can be shown clearly, that all of the light curves except of SN 1991bg (explain below) require positron kinetic energy deposition in order to give a reasonable agreement. Without the energy deposition, it is quite obvious that the light curve is too dim to explain the observe light curve at \(t\geq200^d\) (Colgate, Petschek, Kreise 1980; Capellaro et al. 1997; Ruiz-Lapuente & Spruit 1997).

We show \(\gamma\)-ray energy deposition at \(t\geq60^d\) can hardly be used to distinguished light
curve shape between various models, except to differentiate between extreme models such as between low (PDD1b) and high explosion energy models or between low sub-Chandrasekhar mass (i.e. ONeMg) and Chandrasekhar mass (i.e. W7) models. A similar situation also ensues in the epoch when positron kinetic energy deposition is dominant and for the case of magnetic field in the ejecta being radially combed outward. In the case of turbulence magnetic field, the usefulness of the late time light curve to differentiate models is moderately improved due to the effectiveness of ejecta to slow down and to absorb the kinetic energy of positrons.

The light curves of SN Ia are dominantly powered by the kinetic energy deposition from $\beta^+$ decay of positrons after the nebula becomes optically thin to gamma photons. Before and at the onset of this “positron phase” the positrons have short lifetimes regardless of the field geometry, but as the nebula becomes more tenuous positrons can survive and possibly escape for favorable geometries. The longer the positrons stay as energetic particles, the larger is the deficit of energy deposition relative to the full instantaneous energy deposition. This effect is also observed when there are more positrons escape from the ejecta. Comparing late time light curves of suggested models from early light curve and spectra for particular observed supernovae, the deficit of luminosity relative to instantaneous deposition can be seen in the B and/or the V band light curves of SNe 1992A, 1990N, 1937C, 1972E, 1991T. The phenomena give the evidence that positron take its time in depositing its kinetic energy and possibly moves quite far from its origin and even escapes from the ejecta.

Further detail comparisons of the calculated light curves of positron energy deposition in radial and tangled magnetic field configurations of type Ia models with the observed V and B band light curves show that the radial field configuration (or synonymously the weak field configuration) produces a better agreement than does the tangled magnetic field
configuration, which produces light curves far too flat. The agreement that requires radial field configuration is exhibited by the observed light curves of SN 1992A, SN 1937C, SN 1990N, SN 1972E, and SN 1991T. Models with tangled magnetic field configuration produce a flatter and brighter light curves than the radial field configuration due to the more energy deposition. There are a number of potential sources which can flatten the curves further, but steepening the curves such as by IRC is difficult without color evolution, which to date has not been observed in SN Ia light curve. These facts strengthen the argument that positron escape occurs in SN Ia ejecta.

Fitting observed light curves of SN 1993L, SN 1994D, and SN 1986G give ambiguous results that it is not clear which of the radial or the tangled magnetic configuration model can give acceptable fit. The ambiguity is mostly due to the fluctuation in the observed B and V band light curves. The strongest indication for the tangled magnetic configuration seems to be shown by the SN 1989B observed light curve, however there is a possibility that there is a contribution from a light echo at late times.

SN 1991bg is somewhat a special case that not all SN 1991bg observed light curves agree with each other completely. Two light curves (Turatto et al. 1996; Filippenko et al. 1992) agree with each other, but no model that we have can give a reasonable fit to the light curves unless we unphysically impose no positron kinetic energy deposition in the ejecta. The light curve observed by Leibundgut et al. (1993) can be fit reasonably well with model PDD54 and W7, but we cannot determine the magnetic field configuration in the ejecta because of no observation done by Leibundgut et al. (1993) beyond day 200.

Based on the shape of SN 1937C, SN 1972E, and SN 1992A’s light curves, which all follow the predictions of the radial field configuration model, we conclude that in these supernovae the positrons escape with the most efficient transparency as if the positrons moved in a straight line from their origins to the surface and deposit a minimum of their
kinetic energy as they escape. These supernovae show that type Ia SNe can be a dominant source of the diffuse Galactic 511 keV line fluxes.

To better quantify the suggestion that type Ia supernova may be the main source of positrons that produce the observed Galactic 511 keV line fluxes. We present the number or fraction of positrons that escape from Ia models. The values are in agreement with the values calculated by CL, who demonstrated that the radial magnetic field scenario can easily provide the needed positrons to explain the Galactic annihilation line fluxes.

The Galactic 511 keV annihilation line flux distribution has a definite bulge component (Purcell et al. 1997). SN Ia positrons from $^{56}$Co decays may contribute the majority of the bulge flux and a sizable fraction of the entire galactic emission. As the number of SN Ia observed in spiral galaxies increase, the spatial distribution of bulge and disk SNe will be better known. As OSSE maps the galactic center region with increasing exposure and spectral information, the level to which SN Ia positrons escape from SNe may soon be known.

This work is from a dissertation which was submitted to the graduate school of Clemson University by P.A.M. in partial fulfillment of the requirements for the PhD degree in physics. P.A.M. would like to thank P. Ruiz-Lapuente for access to models and for emphasizing the use of bolometric data when available. We thank P. Höflich for access to many models, giving assistance in locating data and for suggestions of models to test against individual SNe. The isotopically complete models provided by K. Nomoto and S. Kumagai were important for many additional applications. P.A.M. thanks D. Jeffery for spectroscopic insight and assistance locating data. We thank P. Pinto for providing us with model DD4 and for useful discussion on ionization fraction and plasma energy loss. This work was supported by NASA grant DPR S-10987C, via sub-contract to Clemson University.
Table 1. SN Ia model parameters.

<table>
<thead>
<tr>
<th>Model Name</th>
<th>Explosion</th>
<th>Mode of</th>
<th>$M_\star$ [M$_\odot$]</th>
<th>$M_{Ni}$ [M$_\odot$]</th>
<th>$E_{kin}$ [10$^{51}$ erg s$^{-1}$]</th>
<th>$t_B$ [days]</th>
<th>$\dot{E}_\gamma(60^d)$ [10$^{42}$ erg s$^{-1}$]</th>
<th>$\dot{E}_\gamma(100^d)$ [10$^{42}$ erg]</th>
<th>$T(\dot{E}<em>{e^+} = \dot{E}</em>\gamma)$ [days]</th>
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<td>W7</td>
<td>deflagration</td>
<td>1.37</td>
<td>0.58</td>
<td>1.24</td>
<td>14.0</td>
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<td>0.45</td>
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<td>1.42</td>
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<td>1.06</td>
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<td>—</td>
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<td>0.57</td>
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<td>1.60</td>
<td>—</td>
<td>1.63</td>
<td>0.49</td>
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<tr>
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<td>0.76</td>
<td>1.61</td>
<td>—</td>
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<td>0.74</td>
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<td>0.62</td>
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<td>19.8</td>
<td>3.30</td>
<td>1.04</td>
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$^a$t$_B$ is the risetime to reach B band maximum.

$^b$\(\dot{E}_\gamma\) refers to the gamma energy deposition rate, \(\dot{E}_{e^+}\) refers to instantaneous deposition of the positron kinetic energy.
<table>
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<th>SN</th>
<th>Host</th>
<th>Photometric Bands</th>
<th>Distance (Mpc)</th>
<th>E(B-V)</th>
<th>Suggested Spectra (m)</th>
<th>Models</th>
<th>Bolometry</th>
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<td>UBV</td>
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<td>3.6±0.2 (48)</td>
<td>1.1 (45)</td>
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<td>94D</td>
<td>NGC 4526</td>
<td>UBVRI</td>
<td>50</td>
<td>16.8 (4)</td>
<td>0.03 (18)</td>
<td>M36 (20)</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>13.7 (50)</td>
<td></td>
<td>SC0.9 (34)</td>
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</table>
Table 2—Continued

| Host Photometric Distance E(B-V) Suggested SN Galaxy Bands Spectra (Mpc) (m) Models Bolometry |
|-------------------------------------------------|-------------------|-------------------|-------------------|-------------------|
| W7 (4)                                         |                   |                   |                   |                   |

\(^a\)W7 was scaled to 1.0 M☉ to fit 93L.

Table 3. Model Fits to SN 1992A.

<table>
<thead>
<tr>
<th>Model Name</th>
<th>Model Type</th>
<th>Bolometric (55(^d)-450(^d)) (\chi^2/\text{DOF})</th>
<th>V Band (55(^d)-950(^d)) (\chi^2/\text{DOF})</th>
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<tbody>
<tr>
<td>W7</td>
<td>R1%</td>
<td>0.84 0.68</td>
<td>23.9</td>
</tr>
<tr>
<td></td>
<td>R3</td>
<td>2.86 2.4 \times 10^{-6}</td>
<td>43.7</td>
</tr>
<tr>
<td></td>
<td>T</td>
<td>2.98 &lt;10^{-6}</td>
<td>49.0</td>
</tr>
<tr>
<td>DD4</td>
<td>R1%</td>
<td>0.86 0.66</td>
<td>26.4</td>
</tr>
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<td></td>
<td>R3</td>
<td>1.56 0.04</td>
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<td></td>
<td>T</td>
<td>2.13 8.2 \times 10^{-6}</td>
<td>43.1</td>
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<tr>
<td>M39</td>
<td>R1%</td>
<td>0.98 0.48</td>
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</tr>
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<td></td>
<td>R3</td>
<td>1.02 0.43</td>
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<td></td>
<td>T</td>
<td>1.42 0.08</td>
<td>29.4</td>
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<tr>
<td>DD23C</td>
<td>R1%</td>
<td>0.73 0.84</td>
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<td></td>
<td>R3</td>
<td>1.33 0.13</td>
<td>30.9</td>
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<td></td>
<td>T</td>
<td>2.03 1.8 \times 10^{-3}</td>
<td>39.9</td>
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<td>W7DT</td>
<td>R1%</td>
<td>1.28 0.16</td>
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<td></td>
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<td>PDD3</td>
<td>R1%</td>
<td>1.14 0.28</td>
<td>37.4</td>
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<td></td>
<td>R3</td>
<td>3.66 &lt;10^{-6}</td>
<td>64.6</td>
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<td></td>
<td>T</td>
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<td>PDD54</td>
<td>R1%</td>
<td>1.06 0.38</td>
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</tr>
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<td></td>
<td>R3</td>
<td>1.19 0.23</td>
<td>24.3</td>
</tr>
<tr>
<td></td>
<td>T</td>
<td>1.73 0.01</td>
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<td>PDD1b</td>
<td>R1%</td>
<td>4.12 &lt;10^{-6}</td>
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<td></td>
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<td>T</td>
<td>4.15 &lt;10^{-6}</td>
<td>61.8</td>
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<td>WD065</td>
<td>R1%</td>
<td>3.34 &lt;10^{-6}</td>
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<td></td>
<td>T</td>
<td>11.3 &lt;10^{-6}</td>
<td>153.2</td>
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<td>HED6</td>
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<td>2.65 1.4 \times 10^{-5}</td>
<td>53.9</td>
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<td>Model Name</td>
<td>Type</td>
<td>$\chi^2$/DOF</td>
<td>Probability</td>
</tr>
<tr>
<td>------------</td>
<td>------</td>
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<td>-------------</td>
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<td>14.5</td>
<td>$&lt;10^{-6}$</td>
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<td>5.97</td>
<td>$&lt;10^{-6}$</td>
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<td>T</td>
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<td>$&lt;10^{-6}$</td>
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<td>2.62</td>
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<td>5.79</td>
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<td>ONeMg</td>
<td>R1%</td>
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<tr>
<td>DET2E6</td>
<td>R1%</td>
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<td>0.16</td>
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<td>R3</td>
<td></td>
<td>1.21</td>
<td>0.22</td>
</tr>
<tr>
<td>T</td>
<td></td>
<td>1.14</td>
<td>0.28</td>
</tr>
</tbody>
</table>

*R1% refers to 1% ionized ejecta with a radial magnetic field, R3 refers to triply ionized ejecta with a radial field, T refers to 1% ionized ejecta with a trapping field.*
<table>
<thead>
<tr>
<th>Model</th>
<th>Radial Survival Fraction [%]</th>
<th>Radial Yield $10^{52}$ e+</th>
<th>Trapped Survival Yield $10^{-4}$</th>
<th>Trapped Yield $10^{50}$ e+</th>
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<tr>
<td>W7</td>
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<td>4.4–13.1</td>
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<td>0.4–6.8</td>
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<td>DD4</td>
<td>1.5–4.6</td>
<td>3.8–11.6</td>
<td>0.04–1.1</td>
<td>0.1–2.8</td>
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<tr>
<td>M35</td>
<td>2.3–5.7</td>
<td>6.2–15.3</td>
<td>1.7–10.4</td>
<td>4.6–28.1</td>
</tr>
<tr>
<td>M36</td>
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<td>4.9–13.7</td>
<td>1.0–17.6</td>
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<td>7.4–15.8</td>
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<td>W7DT</td>
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<td>15.9–28.5</td>
<td>42.7–64.8</td>
<td>133–187</td>
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<td>PDD3</td>
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<td>0.07–1.7</td>
<td>0.18–4.1</td>
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<td>PDD1b</td>
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<td>0.0–0.0</td>
<td>0.0–0.0</td>
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<td>HED6</td>
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<td>2.2–52.6</td>
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<td>0.3–2.4</td>
<td>0.0–0.0</td>
<td>0.0–0.1</td>
</tr>
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</table>

*Survival refers to escape and/or survival until 2000 d
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Fig. 1.— The outcomes of gamma and X-ray photon interactions in the ejecta. The fraction of the decay energy that is deposited via scattering is labeled $f_{\text{scat}}$, the fraction deposited via photoelectric absorption is labeled $f_{\text{pe}}$. The total fraction deposited is the sum of these two fractions and is labeled $f_{\text{dep}}$. Scattering dominates the energy deposition until $f_{\text{dep}}$ lowers to 0.03, at which time positron kinetic energy deposition dominates.
Fig. 2.— The relative contributions of various modes of positron kinetic energy loss. The upper plot shows the energy losses for 1% ionized ejecta, demonstrating that ionization and excitation of bound electrons dominates. The lower plot shows the energy losses for triply ionized ejecta. For higher levels of ionization, energy losses to the plasma equal and then dominate over the energy losses to bound electrons.
Fig. 3.— The ranges of non-thermal positrons from MC sampling, assuming 1% (open circles) and triply (open boxes) ionized conditions compared with laboratory results in solid media. It is evident that highly ionized gas is more effective at stopping positrons than is a solid. The solid lines are calculated ranges using equation 3 for each level of ionization and assuming the ejecta is pure Fe, the dot-dashed lines are the ranges in pure C. The laboratory measured ranges for solid Aluminum, Silicon and Carbon are taken from ICRU Report #37 (1984). The neutral ejecta stops positrons approximately as does a solid medium.
Fig. 4.— A model generated bolometric light curve for the model W7. The dashed line (D) assumes instantaneous deposition of all decay energy. The dotted line (G) uses the results of the gamma energy deposition only and assumes no deposition of positron energy. Between these two boundaries are the results of the gamma energy deposition coupled with instantaneous positron deposition (thick line, In) and the range of curves for a radial field geometry (dark shading, R) and for a trapping geometry light (shading, T) as the electron ionization fraction varies from $0.01 \leq \chi_e \leq 3$. 
Fig. 5.— The time-integrated luminosities for the radial and trapping field geometries. The radial field permits energy to leave the system at times late enough for positron transport, so only about 96% of the accumulated energy is deposited by 1000$^d$. The trapping field does not permit energy to leave, but energy is stored as the positrons develop appreciable lifetimes. The energy storage is at most 0.4% of the total energy, and at later times most of that energy is deposited, leading to 99.9% of the energy being deposited by 1000$^d$. This late deposition leads to the flattening of the light curve for the trapping field.
Fig. 6.— The fraction of the total energy deposition rate that is contributed by the slowing of positrons for the two field geometries. The solid curve is for a radial field with $^{57}$Co photons, the dot-dashed curve is without $^{57}$Co photons. There is a period of time during which the slowing of positrons dominates the energy deposition. For W7, this period begins after $\sim 250^d$, when the gamma deposition fraction falls below 0.03. For the radial field, at later times positron escape lowers the relative contribution of positron energy deposition. For the trapping field (plotted with long and short dashed lines), positrons dominate out past $1000^d$, regardless of the contributions of $^{57}$Co photons.
Fig. 7.— The rate of energy deposition from the interactions of $^{56}$Ni and $^{56}$Co decay photons with the ejecta. The overall luminosity measures the amount of nickel in the model, the decline from 60$^d$ - 150$^d$ is a measure of the amount of ejecta overlying the nickel and its expansion velocity. The curves do not start at the peak because we have not treated photon diffusion, an effect important before 60$^d$. Note the similarity of curve shapes for all models.
Fig. 8.— The family of bolometric light curves for models with radial magnetic field geometries and 1% ionization, representing the extremes of nickel mass, total mass and kinetic energy. The models are grouped according to explosion type. The curves are normalized to 60$^d$ to show the variation of the shape of the curves. The low-mass models remain brighter than W7 due to the onset of the positron-dominated epoch. PDD1b remains brighter than W7 due to the efficient trapping of gamma photons out to 300 days.
Fig. 9.— Similar to figure 8 with the curves extended to 1000$^d$, and both radial (solid lines) and trapping field geometries (various other lines) are shown. The radial curves form an approximately homogeneous group, the trapping curves flatten according to the $^{56}$Ni location and the velocity structure of the nickel-rich zones.
Fig. 11.— The bolometric magnitudes (solid lines) of five SNe compared with the V (dashed lines) and B (dot-dashed lines) band data.
Fig. 12.— The models DD23c and HED8 fit to the bolometric light curve of SN 1992A (Suntzeff 1996). The solid lines are model-generated bolometric light curves assuming a radial field geometry and 1% ionization, the dot-dashed lines assume a positron trapping field. The early data fixed the normalization and demonstrates that without low-ionization positron escape, low-mass models remain too bright to fit the 300$^d$ and later data. The model DD23c fits the data well for the radial field scenario.
Fig. 13.— The models DD23c and M39 fit to the V band data of SN 1992A (Suntzeff 1996). The data is fit much better by the radial scenario (dark shading) then by the trapping scenario (light shading).
Fig. 14.— The models WD065b, ONeMg, PDD54 and W7 fit to the bolometric data for SN 1991bg (Turatto et al. 1996). The bolometric light curve was generated assuming E(B-V)=0.05 m. The model-generated bolometric light curve assuming a radial field geometry is shown as a solid line, the positron trapping light curve is shown as a dot-dashed line. None of the models fit the entire data-set, PDD54 and W7 approximate the early data.
Fig. 15.— The models PDD54 and W7 fit to the V band data for SN 1991bg (Turatto et al. 1996, Leibundgut et al. 1993, Filippenko et al. 1992). The filled circles are the Turatto et al. data, the open circles are the Fillippenko et al. data, the open boxes are the Leibundgut data. The filled boxes are the Turatto et al. B band data, with $E(B-V)=0.25m$ (a value larger than claimed by Turatto). The dashed lines represent the individual energy deposition contributions from gamma photons and positrons. Both models approximate the Leibundgut data from $120^d$ - $170^d$ and agree with the $545^d$ data point, but fit the Turatto data only if there is no deposition of positron energy.
Fig. 16.— The same as figure 15 for the models WD065b and ONeMg. Both models remain too bright to fit any of the $130^d$ data and later. Both models can fit the Turatto data only if there is no deposition of positron energy.
Fig. 17.— The models W7DN and PDD3 fit to the B and V band data (open and filled circles respectively) of SN 1990N (Lira 1998). No extinction correction was applied to the B data. The data shows appreciable scatter, but is better fit by the radial scenario then by the trapping scenario.
Fig. 18.— The models HED8, W7 and M35 fit to B and V band data of SN 1972E. The filled symbols are V data, the open symbols are B data. The boxes are from Ardeberg & de Groot (1973), the circles are from Kirshner (1975). No extinction correction was applied to the B data. The inset is bolometric data calculated by Axelrod (1980) from Kirshner’s spectra, in units of erg s\(^{-1}\), the solid light curve assumes a radial field with 1% ionization, the dashed light curve assumes a trapping field. All three models show positron escape after 300\(d\).
Fig. 19.— The models W7DT and HECD fit to the V band data (the filled circles are from Lira (1998), the open circles are Schmidt et al. 1994, the open boxes are Cappellaro (1997)) and bolometric light curves of SN 1991T (the bolometric light curve is from Sunzteff 1996 and is in units of erg s$^{-1}$). The light echo was treated to have a constant magnitude. The dashed line shows the radial light curve with no light echo contribution, dot-dashed line shows the same for the trapping light curve. The trapping curves for both models remain too bright to fit the data, even with no contribution from a light echo.
Fig. 20.— The models HED8 and DD4 fit to the B band (open circles) and V band (filled circles) light curves of SN 1993L (CAPP). An extinction correction of $0.2^m$ was applied to the B data. The scatter is considerable, but for HED8, the $350^d+$ data is better fit by the radial scenario. For DD4, the results are the same, but with much less separation between scenarios.
Fig. 21.— The models DET2 and W7 fit to the B band light curve of SN 1937C (Shaefer 1994). There is evidence of positron escape for both models.
Fig. 22.— The models M36 and ONeMg fit to the V band data of SN 1989B (Wells et al. 1994). The inset is bolometric data calculated by Suntzeff (1996) (in units of erg s$^{-1}$). The 60$^d$-120$^d$ behavior was too erratic to be fit by modelling, but the SN settled in to a smoother evolution after 120$^d$. M36 is clearly too faint to explain the late data, the trapping curve of ONeMg comes close to explaining the 320$^d$-370$^d$ data.
Fig. 23.— The models W7, M39, HED6 fit to the B (open symbols) and V (filled symbols) band data of SN 1986G. The circles are from Phillips et al. (1987), the squares are from Cristiani (1992). When an extinction correction of $1.1^m$ was applied to the B data, W7 and M39 fit the data within the uncertainties, while HED6 remains too bright. The data does not extend to late enough epochs to determine the positron transport, but the escape scenario adequately explains the existing data.
Fig. 24.— The models M36 and HED8 fit to the B and V band data of SN 1994D. The early V data (filled circles) are from Patat et al. (1996), the middle V data (filled diamonds) are Tanvir (1997), the late V and B data (filled and open boxes) are CAPP and Cappellaro (1998). No extinction correction was applied to the B data. The late data are fit by both models, differentiation between model types and positron transport scenarios is not possible.
Fig. 25.— The distribution of emitted positron kinetic energies as estimated by Segre (1977, dotted line) compared to the spectrum of escaping positrons from W7, as estimated by Chan and Lingenfelter (filled circles, CL) and this work (solid histogram). Our results agree with CL and demonstrate that the slowing of the positrons leads to the mean energy shifting from 632 keV to 494 keV.