

Late-time supernova light curves: The effect of internal conversion and Auger electrons

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ABSTRACT

Energy release from radioactive decays contributes significantly to supernova light curves. Previous works, which considered the energy deposited by γ -rays and positrons produced by ^{56}Ni , ^{56}Co , ^{57}Ni , ^{57}Co , ^{44}Ti and ^{44}Sc , have been quite successful in explaining the light curves of both core collapse and thermonuclear supernovae. We point out that Auger and internal conversion electrons together with the associated X-ray cascade, constitute an additional heat source. When a supernova is transparent to γ -rays, these electrons can contribute significantly to light curves for reasonable nucleosynthetic yields. In particular, the electrons emitted in the decay of ^{57}Co , which are largely due to internal conversion from a fortuitously low-lying $3/2^-$ state in the daughter ^{57}Fe , constitute an additional significant energy deposition channel. We show that when the heating by these electrons is accounted for, a slow-down in the lightcurve of SN 1998bw is naturally obtained for typical hypernova nucleosynthetic yields. Additionally, we show that for generic Type Ia supernova yields, the Auger electrons emitted in the ground-state to ground-state electron capture decay of ^{55}Fe exceed the energy released by the ^{44}Ti decay chain for many years after the explosion.

Key words: nuclear reactions, nucleosynthesis, abundances — supernovae: general — supernovae: individual (SN 1998bw) — white dwarfs

1 INTRODUCTION

One of the great successes of nuclear astrophysics was demonstrating that the light curves of both thermonuclear (Type Ia) and, at least for late times, core collapse (Type Ib/c, Type II) supernovae are powered by the decay of radionuclides synthesized in the explosion. Quickly following the dynamic explosion and nucleosynthesis phase a supernova enters a state of homologous expansion. The temperature drops during the expansion so that nuclear fusion ceases and radioactive decay is the only means of changing the composition. Pankey (1962), Truran et al. (1967) and Colgate & McKee (1969) first proposed the now widely accepted view that the energy liberated in the decay of radioactive ^{56}Ni followed by the decay of ^{56}Co to stable ^{56}Fe is the most important source for re-heating the supernova ejecta to temperatures high enough to shine brightly in the optical part of the electromagnetic spectrum. Initially, the bulk of the heating is induced by the energetic γ -rays produced in the decays which thermalize and deposit their energy via a number of processes, including Compton scattering and photoelectric absorption. Due to the expansion, however, the column density decreases with time as t^{-2} , and

the ejecta becomes more and more transparent to these high energy photons.

^{56}Co decays predominantly via electron capture, but 19% of all decays proceed via positron emission. The fundamental importance of this positron channel was first pointed out by Arnett (1979). Initially it was assumed that the positrons deposit all of their kinetic energy before forming positronium and annihilating locally (Axelrod 1980). With that assumption, for a generic Type Ia supernovae (SN Ia) model, the ejecta are sufficiently transparent to γ -rays after about ~ 200 days that the ^{56}Co positrons dominate the energy deposition rate (e.g. Woosley et al. 1989; Sollerman et al. 2004). Subsequently, the idea of complete and local energy deposition has been questioned. Chan & Lingenfelter (1993) suggested that as early as a few hundred days after the explosion positrons may begin to escape, especially in the presence of radially combed magnetic fields (see also Milne et al. 1999). However, it has also been argued (e.g. Swartz et al. 1995), that the fraction of positrons which escape cannot be very large since the observed light curves could then not be explained without an additional source of heating.

SN 1987A has demonstrated that light curves can be constructed for nearby supernovae even several years af-

ter the explosion. This has led to the consideration of less abundant but longer lived radioactive species. The most important of these is ^{57}Co , which is expected to be produced in significant amounts as the decay product of the short lived ^{57}Ni . Due to its relatively longer half-life (271.79 days) and the higher opacity of the ejecta to the emitted γ -rays, it may dominate the bolometric light curve, especially of core collapse supernovae, at late times (e.g. Pinto et al. 1988; Woosley et al. 1989). It is widely argued, that the only other radionuclide which noticeably contributes to the bolometric light curve is ^{44}Ti (Woosley et al. 1980; Kumagai et al. 1989). ^{44}Ti has an even longer half-life of 58.9 years (Ahmad et al. 2006), and the short lived daughter ^{44}Sc has a strong positron channel, which means that the ^{44}Ti decay chain can be the dominant energy source at very late times (Kumagai et al. 1989; Woosley et al. 1989).

In section 2, we review the physics of radioactive decay, emphasizing the roles of internal conversion (IC) and Auger electron production. We point out that, while ^{57}Co has no positron channel, due to the nuclear structure of the daughter ^{57}Fe , a significant amount of energy is released in the form of IC and Auger electrons. In section 3, we summarize the current observational status of late time supernova bolometric light curves of SNe Ia and SN 1998bw, a well observed member of the broad-lined SNe Ic class. For both, we sketch the effect electrons emitted in radioactive decays may have. Implications of our study are discussed and our conclusions are drawn in Section 4.

2 RADIOACTIVE DECAY

Most of the mass synthesized by fusion processes in supernova explosions consists of nuclear species in the mass range $A \approx 12 - 70$. The nuclei are typically either stable or lie on the proton-rich side of stability. For the relevant nuclei, fission and α -decay plays no role. The radioactive decay considered here occurs along an isobar towards more neutron rich nuclides in one of two ways, electron capture or positron emission. The first proceeds via the capture of an inner atomic (typically K or L shell) electron by a nuclear proton and the emission of an electron neutrino. The latter proceeds by the decay of a nuclear proton into a neutron and the emission of a positron and an electron neutrino. For both positron emission and electron capture, the transition to the daughter is a statistical process to a distribution of (excited) nuclear levels, with branching ratios given by the transition probabilities.

Following electron capture, the daughter will have an electron hole in its atomic structure. Electrons cascade down to fill the gaps in the lower lying atomic shells and typically a series of characteristic fluorescence X-rays is emitted in the process. However, at every atomic transition, there is the possibility that instead of emission of a photon, the excess energy is carried away by one or several ejected outer electrons (Auger electrons). For ground-state to ground-state electron capture transitions, such as in the decay of ^{55}Fe , no γ -rays or positrons are emitted. Assuming that the neutrino escapes without interactions, in such transitions the Auger electrons and the X-rays constitute the only sources of radioactive heating.

An excited state of the daughter nucleus typically tran-

sitions to lower lying states by emitting γ -ray photons until the ground state is reached. For each transition, however, there exists the additional possibility to de-excite via IC. In this process, the energy difference of the nuclear levels is carried away by the ejection of an inner atomic electron and there is no γ -ray photon emitted. These electrons are called IC electrons. The probability to de-excite via IC, as measured by the IC coefficient $\alpha = \frac{\# \text{ of } e^- \text{ de-excitations}}{\# \text{ of } \gamma \text{ de-excitations}}$, is generally small, but increases for low lying states. In the decay of ^{57}Co in particular, IC electrons are relatively copiously produced, due to the existence of a low-lying nuclear level in the daughter ^{57}Fe . For this 14.4 keV $3/2^-$ state of ^{57}Fe , IC is in fact the preferred mode of de-excitation, with $\alpha = 8.58$.

3 LATE-TIME BOLOMETRIC LIGHT CURVES

Late-time bolometric light curves have already been reconstructed from multi-band photometry for several objects (e.g. Suntzeff 2002; Sollerman et al. 2002, 2004). For reliable reconstruction, the contribution of the UV/optical (*UBVRI*) and near-infrared (*JHK*) bands should be included (*UVOIR* light curve). However, given that near-IR observations are rare at very late epochs, sometimes only *B*-through-*I* band observations are used, applying a near-IR correction extrapolated from earlier epochs (e.g. Sollerman et al. 2002).

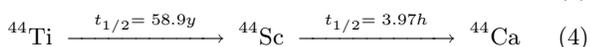
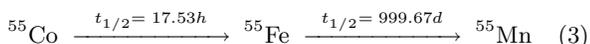
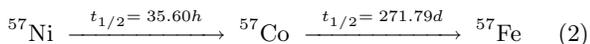
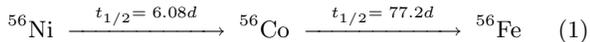
Apart from the heating by various radioactive nuclei, a number of additional effects impact the slope of late-time SN light curves. Most importantly the ejecta become increasingly transparent to γ -rays (Leibundgut & Pinto 1992) and – much later – to positrons (Ruiz-Lapuente & Spruit 1998; Milne et al. 1999), as already mentioned above. This leads to a decline of the light curve steeper than expected for a scenario with a constant energy-deposition fraction. Axelrod (1980) was the first to describe the ‘infrared catastrophe’, which occurs when the temperature in the ejecta drops below a critical value. Thereafter, the cooling is mostly accomplished by fine-structure lines in the mid and far infrared. While this is merely a re-distribution of the emission and has no effect on the true bolometric luminosity, it would show up as a faster decline of the *UVOIR* light curves constructed from observations with a limited wavelength range. Dust formation within the ejecta – though a different physical process – acts in a similar manner. Conversely, a *slow-down* of the bolometric decline rate is observed if ‘freeze-out’ occurs (Fransson & Kozma 1993), i.e., if additional heating is provided by the delayed recombination of electrons at late phases. Interaction of the ejecta with circumstellar material, resulting in a transformation of kinetic energy into light, can have a similar effect. The same is true for possible light echoes, where SN light from an earlier epoch is scattered off interstellar dust clouds towards the observer (Schmidt et al. 1994; Sparks et al. 1999; Patat et al. 2006).

To check for the presence or absence of these effects, it is important to model the contribution of the various radioactive decays to the bolometric luminosity evolution as accurately as possible, including the hitherto neglected IC and Auger electrons whose contributions become important at very late epochs. To illustrate the effects of these elec-

Table 1. Radioactive decay energies (keV decay⁻¹)

Nucleus	Auger e ⁻	IC e ⁻	e ⁺	X-ray
⁵⁷ Co	7.594	10.22	0.000	3.598
⁵⁶ Co	3.355	0.374	115.7	1.588
⁵⁵ Fe	3.973	0.000	0.000	1.635
⁴⁴ Ti	3.519	7.064	0.000	0.768
⁴⁴ Sc	0.163	0.074	595.8	0.030

trons, we consider the following four decay chains.



To circumvent the more complicated treatment of the photon transport, in the subsequent discussion pertinent to very late-time bolometric light curves of different classes of supernovae, we limit ourselves to comparing leptonic (and X-ray) energy injection rates. We do not include the energy produced by the pair annihilation and further assume that the kinetic energy of the leptons is completely thermalized in situ. Thus, possible escape of positrons (or fast electrons) is neglected.

The energy generation rates presented here do not include any heating due to γ -rays and therefore do not accurately predict bolometric light curves. Our approach however does allow for a direct comparison of the relative contributions to the heating of the positrons produced in the decays of ⁵⁶Co and ⁴⁴Sc and the electrons produced in the decays of ⁵⁷Co and ⁵⁵Fe. The relevant energies of the different decay channels are listed in Table 1. These data were extracted from the Chart of Nuclides database, National Nuclear Data Center¹.

3.1 SNe Ia

To date, the thermonuclear SNe with data coverage beyond 500 days are SNe 1991bg (Turatto et al. 1996), 1992A and 1999by (Cappellaro et al. 1997), 2000E (Lair et al. 2006), 2000cx (Sollerman et al. 2004) and 2003hv (Leloudas et al. 2009).² Only three – SNe 2000cx, 2001el (Stritzinger & Sollerman 2007) and 2003hv – have been observed in the near-IR at very late epochs.

SNe Ia lack an extended envelope, and thus become transparent to γ -rays relatively early. In fact, they enter the positron-dominated phase about 150–300 days after the explosion (Leibundgut & Pinto 1992; Milne et al. 2001; Sollerman et al. 2004). Between 300 and 600 days, their UVOIR light curves seem to follow the ⁵⁶Co decay (e.g. Stritzinger & Sollerman 2007), indicating that the majority of the positrons are trapped. During this phase, flux is

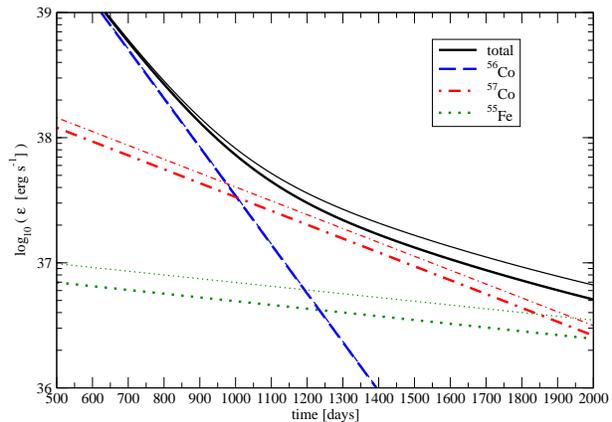


Figure 1. Instantaneous energy generation rates for initial abundances taken from the W7 model of Iwamoto et al. (1999). Thick lines are due to positrons, IC and Auger electrons alone. The thin lines also include the full X-ray dose, which is small even in the limit of complete X-ray trapping. The contribution of electrons and positrons from the decays of ⁴⁴Ti and ⁴⁴Sc is too small to be seen in this figure.

progressively shifted from the optical to the near-IR bands, the *JHK* light curves being flat or declining very slowly. Starting at ~ 600 days there are some indications of a slow-down in the *V* band below the rate expected for ⁵⁶Co decay with full positron trapping (Sollerman et al. 2004; Lair et al. 2006; Leloudas et al. 2009). It has been suggested that a heating source other than ⁵⁶Co, possibly other radioactive species or electron recombination, may be needed to explain this slow-down. We point out that a slow-down in the light curve is expected when the leptonic energy injection from the decay of ⁵⁷Co becomes a significant contribution.

To illustrate this, we plot the leptonic energy generation rates of important long lived isotopes between 500 and 2000 days for theoretical predictions of the yields of the fiducial W7-model (Iwamoto et al. 1999) for a Type Ia supernova (see Fig. 1). For this particular choice of yields, the slope of the light curve begins to deviate appreciably from pure ⁵⁶Co decay after about 800 days. After about 1000 days, the heating due to the electrons produced in the decay of ⁵⁷Co equals the heating from the decay of ⁵⁶Co (mainly due to the positrons). It is also noteworthy that the decay of ⁵⁵Fe contributes significantly after about 1400 days (for this model), but remains below the contribution of ⁵⁷Co until about 2000 days. The contribution of ⁴⁴Ti and its daughter ⁴⁴Sc is below 10^{35} erg s⁻¹ and remains subdominant for many years. In reality, the time at which these effects manifest would depend on the isotopic ratios synthesized in a particular explosion. Nevertheless, we predict that a slow-down must eventually occur for reasonable nucleosynthetic yields.

Electron capture radioactive decay also involves the emission of characteristic fluorescence X-rays (for energies see Table 1). Generally, these X-rays are also neglected as an energy source for the light curve. Since the opacity of the ejecta to X-rays is much higher compared to γ -rays, some part of this X-ray radiation may be trapped; therefore this contributes to the heating. To properly quantify this would require detailed radiation transport simulations including realistic X-ray opacities. However, even under the

¹ <http://www.nndc.bnl.gov/chart/>

² For two other SNe Ia with observations extending to ~ 2000 days, SN 1991T (Schmidt et al. 1994) and SN 1998bu (Cappellaro et al. 2001), light echoes dominate the late-time emission after ~ 500 days.

extreme assumption that the X-rays deposit all their energy (see thin lines in Fig. 1), their contribution is small and our conclusions are not strongly affected.

3.2 SN 1998bw

SN 1998bw is the first known example of a SN associated with a γ -ray burst (Galama et al. 1998). Spectroscopically it lacked any evidence of H or He, and therefore it was classified as a SN Ic. It proved to be an unusually energetic explosion of a massive, stripped stellar core ($\geq 10 M_{\odot}$; Patat et al. 2001; Nakamura et al. 2001b; Maeda et al. 2002). Strong asymmetry was inferred from an analysis of nebular spectra (Maeda et al. 2006). This asymmetry together with the high ejecta velocities and the lack of an extended envelope help to reduce the γ -ray opacity, so that by 1000 days almost all γ -rays escape freely (the models of Nakamura et al. (2001a) suggest that 1998bw enters the positron dominated phase after ~ 400 days).

Core collapse supernovae synthesize isotopes in different ratios compared to SNe Ia, in particular they produce more ^{44}Ti . Nakamura et al. (2001b) calculated nucleosynthetic yields for hypernovae like 1998bw. Their 30 Bethe explosion energy, $10 M_{\odot}$ He-core model predicts a ^{57}Ni to ^{56}Ni mass ratio $\mathcal{R}^{57/56} \approx 0.0366$, ~ 1.5 times the solar value for the ^{57}Fe to ^{56}Fe ratio (which is 0.0234; Lodders 2003). The isotopic ratios for the asymmetric model of Maeda et al. (2002) are similar, albeit with a slightly higher contribution of ^{44}Ti . Höflich et al. (1999) proposed an alternative, highly asymmetric explosion scenario that requires only $0.2 M_{\odot}$ of ^{56}Ni .

After modeling the UVOIR light curve to ~ 1000 days after the explosion, Sollerman et al. (2002) showed that a simple model without contributions from freeze-out effects, circumstellar interaction, accretion by a central compact object or light echoes requires a ^{57}Ni to ^{56}Ni ratio ~ 13.5 times greater than solar. This implies a discrepancy of almost one order of magnitude between the value of $\mathcal{R}^{57/56}$ expected from explosive nucleosynthesis and that suggested by the light curve modeling. However, as we now demonstrate, this discrepancy reduces if IC and Auger electrons are included in the light-curve calculations.

In Fig. 2 we show the combined leptonic and X-ray luminosity corresponding to yield predictions for the aforementioned Nakamura et al. (2001b) model. The non- γ -ray heating due to ^{57}Co is the dominant contribution between ~ 1000 and 1600 days. It is remarkable that this very simplistic approach naturally reproduces the observed slow-down of the light curve at ~ 900 days (see Fig. 2) without the need to invoke any abundance enhancements.

4 DISCUSSION AND CONCLUSIONS

We conclude that the electrons produced in the decay of ^{57}Co constitute a significant energy source for both stripped core collapse and thermonuclear supernovae and should be included in codes that model their late-time light curves. Fortunately, the vast majority of the energy injected via these processes is in the form of primary IC/Auger electrons with energy $\gtrsim 1\text{keV}$. Since the energy deposition channels from such high energy electrons are independent of the input

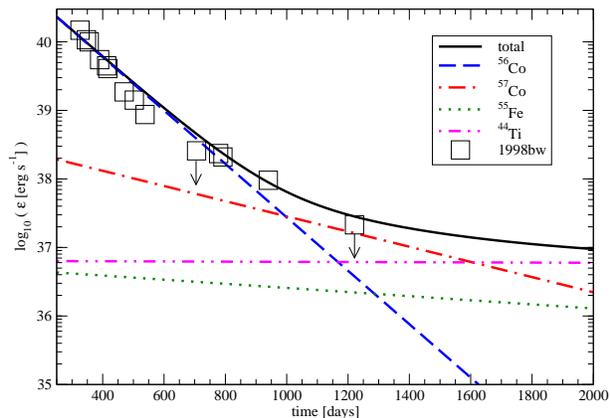


Figure 2. Instantaneous energy generation rates due to radioactivity for initial abundances taken from the 30 Bethe $10 M_{\odot}$ He-core hypernova model of Nakamura et al. (2001b). Only leptons and X-rays (which are small compared to the leptonic contribution) are included (i.e. no γ -ray contribution or freeze-out effects are considered). Squares are the data of 1998bw of Sollerman et al. (2002). Arrows represent 3σ upper limits. There are no free parameters.

electron spectrum (Kozma & Fransson 1992), this means that standard methods for treating e.g. primary Compton electrons are directly applicable.

We suggest that owing to the neglect of the heating due to electrons described in this paper, masses previously derived for ^{44}Ti and ^{57}Ni from light curves should be regarded as upper limits. In particular, a reasonable production factor $\mathcal{R}^{57/56}$ naturally explains the slow-down in the lightcurve of 1998bw without the need to invoke extreme super solar values. In addition, we predict that after ~ 1400 days, the decay of ^{55}Fe causes a further slow-down of SNe Ia light curves, even though it proceeds via a ground-state to ground-state transition. In a scenario with a large escape fraction of the more energetic positrons, the effect may be noticeable even earlier.

We limit our discussion in Section 3 to particular classes of SNe in which the ejecta are expected to be nearly optically thin to γ -rays at the relevant epochs (~ 1000 days) so that leptonic heating rates are likely to dominate. However, ^{57}Co electrons may also be relevant to more complex cases, including SNe II. SN 1987A (Type II-P) is the only SN with a bolometric light curve extending from the earliest stages all the way to the remnant phase (Suntzeff et al. 1992; Suntzeff 1997). The isotopic ratios of the important radionuclides for SN 1987A are not very different from the predictions for a hypernova (Nakamura et al. 2001b) and the differential effect of neglecting the leptonic energy deposition from ^{57}Ni must act in the same sense (i.e. it will lead to an overestimation of $\mathcal{R}^{57/56}$). However, this effect is complicated by the large envelope mass, which means the ejecta are not fully transparent to γ -rays at the relevant epoch (Woosley et al. 1989) and thus leptonic contributions play a smaller role in heating the ejecta. To quantify this requires detailed calculations involving both γ -ray transport and freeze-out effects (Fransson & Kozma 1993), which we defer to future work.

The additional heating channel pointed out in this paper allows, in principle, for a larger escape fraction of positrons than previously suggested by modeling late-time

light curves – as noted in Section 1. Past analyses of light curves have deduced that the escape fraction must be very small, but any additional heating source relaxes this constraint somewhat. This may have implications for understanding the origin of the Galactic population of positrons and the strength of the Galactic 511 keV annihilation line.

Our calculations have used atomic data for neutral atoms. Although matter in supernova remnants is ionized, for light or moderate ionization states, we do not expect the IC and Auger decay energies to change significantly, since most of the physics concerns the K, L, and inner M shell. For very high levels of ionization, the numbers listed in Table 1 are inappropriate. However, high levels of ionization are not expected at late times (e.g. Kozma & Fransson 1998) unless the ejecta is shock-ionized by interaction with circumstellar material, a scenario which would, in any case, likely prohibit reliable abundance determination because of the need to separate the contributions from the shock heating and radioactive decays to the bolometric light curve.

The case of SN 1987A (not a very luminous object, but at a distance of only ~ 50 kpc in the LMC) demonstrates that SN explosions of any type exploding within the Local Group can be followed for many years after the explosion. Adopting an average rate of ~ 0.9 SNe $(100 \text{ yr})^{-1}$ $(10^{10} L_{\odot}^B)^{-1}$ in spiral galaxies (Cappellaro et al. 1999), and a Local-Group B -band luminosity of $\sim 6 \times 10^{10} L_{\odot}^B$ (de Vaucouleurs et al. 1976; Sandage & Tammann 1981), statistically a few Local-Group SNe are expected every 100 years. It is therefore plausible that the effects discussed in this paper can be observed unambiguously in the future.

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