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 56Ni, 56Co, 57Ni, 57Co, 44Ti and 44Se, 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 57Co, which are largely due to internal conversion from a fortuitously low-lying 3/2− state in the daughter 57Fe, constitute an additional significant energy-deposition channel. We show that when the heating by these electrons is accounted for, a slow-down in the light curve 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 55Fe exceed the energy released by the 44Ti 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 (SNe) are powered by the decay of radionuclides synthesized in the explosion. Quickly following the dynamic explosion and nucleosynthesis phase, an SN 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, Arnett & Cameron (1967) and Colgate & McKee (1969) first proposed the now widely accepted view that the energy liberated in the decay of radioactive 56Ni followed by the decay of 56Co to stable 56Fe is the most important source for re-heating the SN 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 \( r^{-2} \), and the ejecta becomes more and more transparent to these high energy photons.

56Co decays predominantly via electron capture, but 19 per cent 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 (SNe Ia) model, the ejecta are sufficiently transparent to γ-rays after about \( \sim 200 \) d that the 56Co positrons dominate the energy-deposition rate (e.g. Woosley, Hartmann & Pinto 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, The & Leising 1999). However, it has also been argued (e.g. Swartz, Sutherland & Harkness 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 SN even several years after the explosion. This has led to the consideration of less abundant but longer lived radioactive species. The most important of these is 57Co, which is expected to be produced in significant amounts as the decay product of the short-lived 57Ni. Due to its relatively longer half-life (271.79 d) and the higher opacity of the ejecta to the emitted γ-rays, it may dominate...
the bolometric light curve, especially of core collapse SNe, at late times (e.g. Pinto, Woosley & Ensim 1988; Woosley, Hartmann & Pinto 1989). It is widely argued that the only other radionuclide, which noticeably contributes to the bolometric light curve, is $^{44}$Ti (Woosley, Weaver & Taam 1980; Kumagai et al. 1989). $^{44}$Ti has an even longer half-life of 58.9 yr (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 SN 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 SN 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 $\alpha$-decay play 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 $\gamma$-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 transitions to lower lying states by emitting $\gamma$-ray photons until the ground state is reached. For each transition, however, there exists the additional possibility of de-exciting 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 $\gamma$-ray photon emitted. These electrons are called IC electrons. The probability of de-exciting via IC, as measured by the IC coefficient $\alpha = \frac{\text{nr} \text{ of } e^- \text{ de-excitation}}{\text{nr} \text{ of } \gamma \text{ de-excitation}}$, 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 $2^-$ 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 multiband photometry for several objects (e.g. Sollerman et al. 2002, 2004; Suntzeff 2002). For reliable reconstruction, the contribution of the UV/optical ($UBVRI$) and near-infrared (near-IR) ($JHK$) 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 $\gamma$-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-IR. While this is merely a redistribution 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 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 electrons, we consider the following four decay chains:

$$^{56}\text{Ni} \rightarrow ^{56}\text{Co} \rightarrow ^{56}\text{Fe} \quad (1)$$

$$^{57}\text{Ni} \rightarrow ^{57}\text{Co} \rightarrow ^{57}\text{Fe} \quad (2)$$

$$^{55}\text{Co} \rightarrow ^{55}\text{Fe} \rightarrow ^{55}\text{Mn} \quad (3)$$

$$^{44}\text{Ti} \rightarrow ^{44}\text{Sc} \rightarrow ^{44}\text{Ca} \quad (4)$$

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 SNe, 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 $\gamma$-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 $^{56}$Co and $^{44}$Sc and the electrons produced in the decays of $^{57}$Co and $^{56}$Fe. The relevant energies of the different decay channels are listed in Table 1. These data were extracted from the Chart of Nuclides data base, National Nuclear Data Center.\(^1\)

3.1 SNe Ia

To date, the thermonuclear SNe with data coverage beyond 500 d 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 d after the explosion (Leibundgut & Pinto 1992; Milne, The & Leising 2001; Sollerman et al. 2004). Between 300 and 600 d, their UVOT light curves seem to follow the $^{56}$Co decay (e.g. Stritzinger & Sollerman 2007), indicating that the majority of the positrons are trapped. During this phase, flux is progressively shifted from the optical to the near-IR bands, the $^{56}$Co light curves being flat or declining very slowly. Starting at ~600 d, there are some indications of a slow-down in the V band below the rate expected for $^{56}$Co decay with full positron trapping (Sollerman et al. 2004; Lair et al. 2006; Leloudas et al. in preparation). It has been suggested that a heating source other than $^{56}$Co, 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 $^{57}$Co becomes a significant contribution.

To illustrate this, we plot the leptonic energy generation rates of important long-lived isotopes between 500 and 2000 d for theoretical predictions of the yields of the fiducial W7 model (Iwamoto et al. 1999) for a Type Ia SN (see Fig. 1). For this particular choice of yields, the slope of the light curve begins to deviate appreciably from pure $^{56}$Co decay after about 800 d. After about 1000 d, the heating due to the electrons produced in the decay of $^{57}$Co equals the heating from the decay of $^{56}$Co (mainly due to the positrons). It is also noteworthy that the decay of $^{55}$Fe contributes significantly after about 1400 d (for this model), but remains below the contribution of $^{57}$Co until about 2000 d. The contribution of $^{44}$Ti and its daughter $^{44}$Sc is below 10\(^{+5}\) 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 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 an 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 an SN Ic. It proved to be an unusually energetic explosion of a massive, stripped stellar core (≥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 d almost all γ-rays escape freely (the models of Nakamura et al. 2001a suggest that 1998bw enters the positron-dominated phase after ~400 d).

Core collapse SNe 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 such as 1998bw. Their 30 Bethe explosion energy, 10 $M_{\odot}$ He-core model predicts a $^{57}$Ni to $^{56}$Ni mass ratio $R_{^{57/56}} \approx 0.0366$, ~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, Wheeler & Wang (1999) proposed an alternative, highly asymmetric explosion scenario that requires only 0.2 $M_{\odot}$ of $^{56}$Ni.

\(^1\) http://www.nndc.bnl.gov/chart/
\(^2\) For two other SNe Ia with observations extending to ~2000 d, SN 1991T (Schmidt et al. 1994) and SN 1998bu (Cappellaro et al. 2001), light echoes dominate the late-time emission after ~500 d.
Instantaneous energy generation rates due to radioactivity for initial abundances taken from the 30 Bethe $10M_\odot$ 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 $\gamma$-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.

After modelling the UVOIR light curve to $\sim 1000$ d 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, $\sim 13.5$ times greater than solar. This implies a discrepancy of almost one order of magnitude between the value of $R^{57/56}$ expected from explosive nucleosynthesis and that suggested by the light-curve modelling. 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-$\gamma$-ray heating due to $^{57}$Co is the dominant contribution between $\sim 1000$ and 1600 d. It is remarkable that this very simplistic approach naturally reproduces the observed slow-down of the light curve at $\sim 900$ d (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 SNe 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 $\gtrsim 1$ keV. Since the energy-deposition channels from such high energy electrons are independent of the input electron spectrum (Kozma & Fransson 1992), this means that standard methods for treating other fast electrons (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 $R^{57/56}$ naturally explains the slow-down in the light curve of 1998bw without the need to invoke extreme supersolar values. In addition, we predict that after $\sim 1400$ d, 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 $\gamma$-rays at the relevant epochs ($\sim 1000$ d) 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 $R^{57/56}$). However, this effect is complicated by the large envelope mass, which means that the ejecta are not fully transparent to $\gamma$-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 $\gamma$-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 modelling 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 SN 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 shells. 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 $\sim 50$ kpc in the Large Magellanic Cloud (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 $\sim 0.9$ SNe (100 yr)$^{-1}$ ($10^{10}$ $L_\odot$)$^{-1}$ in spiral galaxies (Cappellaro, Evans & Turatto 1999) and a Local-Group B-band luminosity of $\sim 6 \times 10^{10}$ $L_\odot$ (de Vaucouleurs & Corwin 1976; Sandage & Tammann 1981), statistically a few Local-Group SNe are expected every 100 yr. It is therefore plausible that the effects discussed in this paper can be observed unambiguously in the future.

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REFERENCES


Galama T. J. et al., 1998, Nat, 395, 670


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