Theoretical light curves of Type II-P supernovae and applications to cosmology

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ABSTRACT

Based on an extensive grid of stellar models between 13 and 25 $M_\odot$ and a wide range of metallicities, we have studied the light curves of core collapse supernovae, their application to cosmology and their evolutionary effects with redshift. The direct link between the hydrodynamics and radiation transport allows us to calculate monochromatic light curves.

With decreasing metallicity, $Z$, and increasing mass, progenitors tend to explode as compact blue supergiants (BSG) and produce subluminous supernovae that are approximately 1.5 mag dimmer than normal Type II supernovae (SNe II) with red supergiant (RSG) progenitors. Progenitors with small masses tend to explode as RSGs even at low $Z$. The consequence for testing the chemical evolution is obvious, namely a strong bias when using the statistics of core collapse supernovae to determine the history of star formation.

Our study is limited in scope with respect to the explosion energies and the production of radioactive Ni. Within the class of extreme SNe II-P supernovae, the light curves are rather insensitive with respect to the progenitor mass and explosion energy compared with analytic models based on parametrized stellar structures. We expect a wider range of brightness due to variations in $^{56}$Ni because radioactive energy is a significant source of luminosity. However, the overall insensitivity of light curves may allow their use as quasi-standard candles for distance determination.

Key words: stars: evolution – stars: interiors – supernovae: general – distance scale.

1 INTRODUCTION

Core collapse supernovae (SNe) are thought to be the final results of stellar evolution for stars with main-sequence masses $\gtrsim 10$ $M_\odot$ with short evolutionary time-scales compared with the age of the Universe even at high $z$ (Maza & van den Bergh 1976; Tammann 1982; Woosley & Weaver 1986). These objects occur soon after the initial star formation period and, therefore, can be used to probe the structure of the Universe at high $z$. These very distant supernovae are all expected to be a variety of core collapse supernovae. For example, at $z \sim 5–10$, galaxies are expected to be small and dim and core collapse supernovae may be the brightest objects in the Universe (Miralda-Escudé & Rees 1997).

The light curves (LCs) and spectra depend sensitively on the initial stellar mass, metallicity, mass loss and explosion energy. They show a wide range of brightness, up to 6 mag, and properties of their LCs (Young & Branch 1989; Patat et al. 1993, 1994; Filippenko 2000) that prevent their use as standard candles. However, our knowledge of the event is improving and it may be possible to derive the absolute magnitude in a similar way as for Type Ia supernovae if appropriate empirical correlations can be identified.

There is general agreement that the explosion of a massive star is caused by the collapse of its central parts into a neutron star or a black hole. The mechanism of the energy deposition into the envelope is still debated. The process probably involves the bounce and the formation of a prompt shock (e.g. Van Riper 1978; Hillebrandt 1982), radiation of the energy in the form of neutrinos (e.g. Bowers & Wilson 1982), the interaction of the neutrinos with the material of the envelope and various types of convective motions (e.g. Herant et al. 1994; Burrows, Hayes & Fryxell 1995; Müller & Janka 1997; Janka & Müller 1996), rotation (e.g. LeBlanc & Wilson 1970; Saenz & Shapiro 1981; Mönchmeyer et al. 1991) and magnetic fields (e.g. LeBlanc & Wilson 1970; Bisnovatyi-Kogan 1971).

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The analysis of core collapse supernovae and their use for cosmology is further complicated by the mounting evidence that the explosions of massive stars (core collapse SNe) are highly aspherical and, consequently, that the brightness depends on their orientation with respect to the observer (e.g. Höflich 1991b). (i) The spectra (e.g. SN87A, SN93J, SN94I, SN99em) are significantly polarized, indicating asymmetric envelopes (Méndez et al. 1988; Höflich 1991b; Jeffrey 1991; Wang et al. 1996; Wang, Wheeler & Höflich 1999). The degree of polarization tends to vary inversely with the mass of the hydrogen envelope, being maximum for SNe Ib/c events with no hydrogen (Wang et al. 2000; Leonard et al. 2002a). For supernovae, with good time and wavelength coverage, the orientation of the polarization vector tends to remain constant both in time and in wavelength. This suggests that there is a global symmetry axis in the ejecta (Leonard et al. 2002b). (ii) Observations of SN 1987A showed that radioactive material was brought to the hydrogen-rich layers of the ejecta very quickly during the explosion (Tueller et al. 1991). (iii) The remnant of the Cas A supernova shows rapidly moving oxygen-rich matter outside the nominal boundary of the remnant and evidence for two oppositely directed jets of high-velocity material (Fesen & Gunderson 1997). (iv) Recent X-ray observations from the Chandra satellite have shown an unusual distribution of iron and silicon group elements with large-scale asymmetry in Cas A (Hughes et al. 2000). (v) After the explosion, neutron stars are observed with velocities up to 1000 km s\(^{-1}\) (Strom et al. 1995).

As a result of the difficulty of modelling core collapse SNe from first principles, a very different line of attack on the explosion problem has been used extensively and has proved to be successful in aiding our understanding of the supernova problem, and of SN 1987A in particular (Arnett et al. 1990; Hillebrandt & Höflich 1991). The difference of characteristic time-scales of the core (1 s or less) and of the envelope (hours to days) allows us to divide the explosion problem into two largely independent parts – the core collapse and the ejection of the envelope. By assuming the characteristics of the energy deposition into the envelope during the core collapse, the response of the envelope can be calculated. Thus, one can study the observational consequences of the explosion and deduce characteristics of the core collapse and the progenitor structure. This approach has been extensively applied within the framework of the one-dimensional (1D) spherically symmetric formulation. The major factors influencing the outcome have been found to be the explosion energy and the progenitor structure. Recently, the same approach has been applied in multidimensions to investigate the effects of asymmetric explosions (e.g. Höflich, Khokhlov & Wang 2001). First results show that both asymmetric density structures and ejections are keys for our understanding of the global asymmetries in core collapse supernovae.

Despite these problems, methods have been developed to use these objects for distance determinations, namely, SNe II that have retained their H-rich envelope. SNe II represent an important complement to SNe Ia as a technique to measure cosmological distances. First results show that both asymmetric density structures and ejections of massive stars (core collapse SNe) are highly aspherical and, consequently, that the brightness depends on their orientation with respect to the observer (e.g. Höflich 1991b).
focused on core collapse supernovae to answer the following questions: how do the LCs of core collapse supernovae depend on the metallicity that is expected to decrease with redshift? Can we identify a subclass among the core collapse supernovae that may be used as quasi-standard candles, and what accuracy do we expect? Can this subclass be identified purely by the LCs, without a follow-up that requires us to go much fainter than maximum light?

The outline of the paper is as follows. In Section 2 the numerical methods used for the evolution, explosion and light-curve computations are described. In Section 3 the influence of the progenitor properties and explosion parameters on the LC is analysed, and finally, in Section 4, we highlight the main conclusions and limitations of our study.

2 NUMERICAL METHODS

2.1 Stellar evolution

All the pre-supernova models adopted in this paper have been computed by means of the evolutionary code FRANEC 4.2 (for details see Chiefi & Straniero 1989; Straniero, Chiefi & Limongi 1997; Chiefi, Limongi & Straniero 1998; Limongi, Straniero & Chiefi 2000; Chiefi & Limongi 2002). FRANEC is a hydrostatic evolutionary code in which the set of equations describing the physical structure of the star (assuming spherical symmetry) and the chemical evolution of the matter, due to the nuclear reactions, are fully coupled and integrated simultaneously by means of a classical Newton–Raphson method. The nuclear network includes 41 isotopes for the H burning, 88 isotopes for the He burning and 179 isotopes for the more advanced phases. Nuclear reaction rates are taken from Thielemann’s data base (private communication). For the $^{12}\text{C}(\alpha, \gamma)^{16}\text{O}$ reaction we adopt the value from Caughlan et al. (1985), which is close to the upper limit compatible with presently available measurements for this rate. The weak interaction rates as a function of the temperature and density are derived from Fuller, Fowler & Newman (1980, 1982, 1985).

The extension of the convective regions is fixed by means of the Schwarzschild criterion and no mechanical overshoot is allowed. Induced overshooting and semiconvection during core He burning are taken into account (Castellani et al. 1985). In the convective layers the temperature gradient is evaluated by means of the mixing length theory as described by Cox & Giuli (1968). A time-dependent mixing scheme is used, similar to that introduced by Sparks & Endal (1980). We have also developed a specific algorithm that can handle the evolution of those isotopes for which the nuclear burning lifetime becomes comparable to or lower than the mixing time-scale (see Chiefi et al. 1998).

Electron screenings are taken from Graboske et al. (1973) and De Witt, Graboske & Cooper (1973) for the weak, intermediate and intermediate–strong regime, and from Itoh, Totsuji & Ichimaru (1977) and Itoh et al. (1979) for the strong regime. The equation of state (EOS) is that described by Straniero (1988) and updated by Straniero et al. (1997). It includes Coulomb corrections, quantum-relativistic effects on the electron component and electron–positron pair production. Radiative opacity coefficients are derived from Kurucz (1991), Alexander & Ferguson (1994), Igleísias, Rogers & Wilson (1992) (OPAL) and from the Los Alamos Opacity Library (LAOL) (Huebner et al. 1977). A scaled solar mixture (Grevesse 1991) is adopted. Opacity coefficients due to thermal conductivity are derived from Itoh et al. (1983). Energy losses due to photo, pair and plasma neutrinos are taken into account following Munakata, Kohyama & Itoh (1985, 1986). Bremsstrahlung neutrinos are obtained following Dicus et al. (1976) as corrected by Richardson et al. (1982). Energy losses due to recombination processes are included using the prescriptions of Beaudet, Petrosian & Salpeter (1967).

In this work, all the models are evolved at constant mass and no rotation has been taken into account. The effects of rapid rotation on the evolution of massive stars have been studied recently in 1D by Heger, Langer & Woosley (2000) and Meynet & Maeder (2000, 2003). As discussed in the introduction, the explosion mechanism itself could be based on rotation but the effect on the hydrodynamics of the H-rich envelope is expected to be small. However, anisotropies in Ni distribution and, thus, in ionization may cause anisotropic luminosities of the order of 10 per cent (Höflich 1991b; Höflich et al. 2001).

2.2 Explosion and light-curve models

The explosions are calculated using our 1D radiation–hydrodynamics code, including nuclear networks (Höflich & Khokhlov 1996, and references therein). This code solves the hydrodynamical equations explicitly by the piecewise parabolic method (Colella & Woodward 1984) and includes the solution of the frequency-averaged radiation transport implicitly via momentum equations, expansion opacities (see below) and a detailed equation of state. For high densities and temperatures ($\geq 1$ g cm$^{-3}$, $\geq 10^7$ K), relativistic effects are taken into account and full ionization is assumed. For lower densities and temperatures, ionization processes are included under the assumption of local thermodynamical equilibrium but relativistic effects are neglected.

The explosion is triggered artificially by depositing energy at a mass location near the edge of the iron core. After the initial phase of the explosion, i.e. shortly before the shock front reaches the stellar surface, the nuclear reactions are switched off and $\gamma$ ray transport is included via a Monte Carlo scheme. Both monochromatic and bolometric LCs are calculated using a scheme recently developed, tested and widely applied to SNe Ia (Höflich, Wheeler & Thielemann 1998 and references therein). In order to allow for a more consistent treatment of scattering, we solve both the (two lowest) time-dependent, frequency-averaged radiation momentum equations for the radiation energy and the radiation flux, and a total energy equation. At each time-step, we then use $T(r)$ to determine the Eddington factors and mean opacities by solving the frequency-dependent radiation transport equation in the comoving frame and integrate to obtain the frequency-averaged quantities. The averaged opacities are calculated under the assumption of local thermodynamical equilibrium. Both the monochromatic and mean opacities are calculated using the Sobolev approximation. The scattering, photon redistribution and thermalization terms used in the light-curve opacity calculation are calibrated with non-local thermal equilibrium calculations using the formalism of the equivalent two-level approach (Höflich 1995). About 1000 frequencies and between 550 and 700 depth points are used.

3 RESULTS

3.1 Stellar models

The evolution of selected models in the mass range from 13 to 25 $M_\odot$ and metallicities between $Z = 0$ and 0.02 have been computed from the pre-main sequence to the onset of core collapse without mass loss (see Fig. 1 and Table 1). For low metallicity, Z, models explode as compact BSG ($R_\nu \lesssim 100$ $R_\odot$) rather than as extended RSG ($500 \lesssim R_\nu \lesssim 1500$ $R_\odot$). The metallicity plays a major role in determining the radius of the star because it affects the...
 opacity that determines the super-adiabatic gradient. The greater the opacity, the larger the super-adiabatic gradient and hence the larger the radius of the star. This explains why, for low metallicities, stars explode as BSGs. The lower the metallicity, the lower the opacity of the envelope is and, consequently, the more compact the structure. We find that all the zero-metallicity models end up as BSGs while all the solar metallicity ones become RSGs. At intermediate Z, there is a general trend for the more massive stars to end up as BSGs while the less massive ones end up as RSGs. The limiting mass depends on Z. However, the critical metallicity beyond which a star ends up as an RSG instead of as a BSG depends sensitively on many details, including the treatment of convection, the opacities, rotation and mass loss.

In Table 1 we describe selected properties of the pre-supernova evolutions, namely: the identification name of the models, mnxn, nn is the mass and x refers to metallicity, ‘a’ for solar (Z = 0.02), ‘b’ for Z = 0.001 and ‘z’ for Z = 0 (column 1); the mass in solar units (column 2); the final radius in solar radii (column 3); the metallicity (column 4); BSG versus RSG (column 5); the hydrogen burning lifetime in years (column 6); the helium burning lifetime in years (column 7); the residual lifetime following the central H exhaustion up to the iron core collapse (column 8); the final surface mass fraction of H (column 9) and of He (column 10).

Table 1. Selected quantities of some of the stellar models.

| Model | Mass | \( R_{\text{fin}} \) (R\(_{\odot}\)) | Z  | BSG versus RSG | \( \tau_{\text{H}} \) (yr) | \( \tau_{\text{He}} \) (yr) | \( \tau_{\text{adv}} \) (yr) | \( H_{\text{sup}} \) | \( H_{\text{esup}} \) |
|-------|------|-----------------|----|----------------|-----------------|-----------------|-----------------|--------------|--------------|
| m13a  | 13   | \( 5.52 \times 10^{2} \) | 2 \times 10^{-2} | RSG | 1.26 \times 10^{7} | 1.92 \times 10^{6} | 6.57 \times 10^{4} | 0.649 | 0.331 |
| m15a  | 15   | \( 6.71 \times 10^{2} \) | 2 \times 10^{-2} | RSG | 1.08 \times 10^{7} | 1.45 \times 10^{6} | 3.87 \times 10^{4} | 0.638 | 0.342 |
| m20a  | 20   | \( 9.40 \times 10^{2} \) | 2 \times 10^{-2} | RSG | 7.50 \times 10^{6} | 9.53 \times 10^{5} | 2.29 \times 10^{4} | 0.609 | 0.371 |
| m25a  | 25   | \( 1.19 \times 10^{3} \) | 2 \times 10^{-2} | RSG | 5.97 \times 10^{6} | 6.99 \times 10^{5} | 1.67 \times 10^{4} | 0.593 | 0.387 |
| m13b  | 13   | \( 4.08 \times 10^{2} \) | 1 \times 10^{-3} | RSG | 1.47 \times 10^{7} | 1.80 \times 10^{6} | 6.03 \times 10^{4} | 0.708 | 0.291 |
| m15b  | 15   | \( 1.01 \times 10^{2} \) | 1 \times 10^{-3} | RSG | 1.22 \times 10^{7} | 1.41 \times 10^{6} | 4.17 \times 10^{4} | 0.769 | 0.230 |
| m20b  | 20   | \( 4.60 \times 10^{2} \) | 1 \times 10^{-3} | RSG | 8.84 \times 10^{6} | 8.71 \times 10^{5} | 2.47 \times 10^{4} | 0.769 | 0.230 |
| m25b  | 25   | \( 5.26 \times 10^{2} \) | 1 \times 10^{-3} | RSG | 7.09 \times 10^{6} | 6.69 \times 10^{5} | 1.80 \times 10^{4} | 0.769 | 0.230 |
| m15z  | 15   | \( 2.48 \times 10^{3} \) | 0.0 | RSG | 1.05 \times 10^{6} | 9.27 \times 10^{5} | 5.44 \times 10^{4} | 0.770 | 0.230 |
| m20z  | 20   | \( 2.31 \times 10^{3} \) | 0.0 | RSG | 7.74 \times 10^{6} | 5.76 \times 10^{5} | 2.39 \times 10^{4} | 0.770 | 0.230 |
| m25z  | 20   | \( 3.67 \times 10^{3} \) | 0.0 | RSG | 6.72 \times 10^{6} | 4.96 \times 10^{5} | 1.59 \times 10^{4} | 0.770 | 0.230 |

Fig. 2 shows the chemical composition at the onset of the iron core collapse, for some of the computed stellar models. Fig. 3 illustrates the influence of both metallicity (upper panel) and initial mass (lower panel) on the density profiles. As is well known, the smaller the total mass is, the less compact the star. By comparing Figs 2 and 3 it appears that the last (most external) sudden drop in the density profiles corresponds to the transition to the H-rich envelope. From this point to the surface, the density–mass relation is essentially independent of the initial mass, while, in contrast, it is significantly affected by a variation in metallicity. As will be discussed in more detail in the following sections, such a correlation between the density of the H-rich envelope with the mass and the metallicity of the stellar progenitor has a significant influence on the features of the various LCs, in particular on the plateau phase (namely the first 100–150 d). In fact, during this phase, the H recombination front, which provides the nearly constant luminosity, moves inward (in mass) through the whole envelope.

Another important quantity that characterizes the light curve is the total amount of H present in the envelope. In principle, it depends on the original chemical composition of the star, on the initial mass, on the mass-loss rate and on the efficiency of the various dredge-up episodes occurring during the progenitor lifetime. In Fig. 4 we have reported the final H mass as a function of the total mass for the three different metallicities. Note that the final H mass linearly increases
3.1 Evolutionary models

As the stellar mass increases and the metallicity decreases, we find that the following relation nicely reproduces the results of our stellar evolution calculations:

\[ M_d(M_\odot) = 2.58 + 0.338M(M_\odot) - 50.3Z, \]

where \( M_d, M \) and \( Z \) are the total H mass, the total stellar mass and the metallicity, respectively. Since our models were obtained without mass loss, this relation provides an upper limit for the final amount of H.

3.2 Explosion models

Based on the evolutionary models previously described, we have explored the sensitivity of different characteristics of the light curve on progenitor properties (mass and metallicity) and explosion energy. The explosion is triggered by depositing a given amount of energy at a mass coordinate close to the edge of the iron core of the pre-supernova model, i.e. at approximately 1.4 \( M_\odot \) which, in turn, corresponds to approximately 1000 km in all the models. The injected energy is adjusted to provide the desired final kinetic energy. In all models except one, the final kinetic energy is \( 10^{51} \text{ erg} \) (1 foe), the exception being model m15a; for this model we also consider the case with a final kinetic energy of \( 2 \times 10^{51} \text{ erg} \) (hereafter model m15a2). For test calculations, the explosion energy was deposited as thermal or kinetic energy, but little difference was found between the explosion models.

In general, at a given time after the explosion is triggered, the velocity of the more internal zones of the exploding envelope decreases to the escape velocity. Consequently, these zones eventually and naturally fall back on to the compact remnant. The final mass location between the ejecta and the remnant is defined as the mass cut. The fallback of material on to the central neutron star remained below \( 10^{-3} M_\odot \) except in the more massive models. A significant fallback of 0.1 and 0.47 \( M_\odot \) was obtained for m20a and m25a, respectively. We note that the amount of fallback depends sensitively on the explosion energy. In test calculations for m25a with twice the explosion energy, the fallback was reduced by approximately a factor of 5. In all cases, except for 25 \( M_\odot \), more than a tenth of a solar mass of \(^{56}\text{Ni}\) would be ejected, which is in excess of the typical amount obtained from the observed luminosity of the light-curve tails. For this reason, we introduced an artificial mass cut (more external than the actual mass cut) in the explosion models at approximately 1 d after the explosion, in order to limit the \(^{56}\text{Ni}\) production accordingly. In this work we adopt the typical value of 0.07 \( M_\odot \) (e.g. SN 1987A) for the \(^{56}\text{Ni}\) mass, although some SN II-P are known to have more than a tenth (e.g. SN 1992am, 0.3 \( M_\odot \); Schmidt et al. 1994; 1986I, 1991G, 1992H, Hamuy 2002).

A further restriction of our models is related to the discretization in mass, which is of the order of \( 10^{-3} M_\odot \). A proper resolution of the photosphere during the first few days of the explosion requires a discretization of approximately \( 10^{-5} M_\odot \) (e.g. Müller & Höflich 1991). Consequently, details of the shock breakout are beyond the scope of this study because the photosphere is not well resolved during the early phases.

Table 2 gives the basic parameters and some of the derived quantities for the explosion models and LCs. Consider the first four columns: identification of the model, as in Table 1 (column 1); final kinetic energy after the explosion (column 2); time of the shock breakout in seconds (column 3); and the corresponding temperature \( T_{\text{shock}} \) at the photosphere (column 4).

In Figs 5–7, a typical evolution of the exploding star is given for the example of model m15a. Initially, the shock front propagates...
Table 2. Explosion models and light-curve properties.

| Model   | $E_{\text{kin}}$ (10^50 erg) | $t_{\text{shock}}$ (s) | $\log(T_{\text{shock}})$ | $V_{\text{max}}$ | $\Delta t_{\text{plateau}}$ (d) | $\Delta m_{\text{bump}}$ (mag) |
|---------|-------------------------------|--------------------------|---------------------------|------------------|-------------------------------|-------------------------------|
| m13a    | 10                            | $1.33 \times 10^5$      | 5.5                       | $-17.49$         | 45                            | 0.15                          |
| m15a    | 10                            | $1.21 \times 10^5$      | 5.4                       | $-17.47$         | 66                            | 0.22                          |
| m20a    | 10                            | $2.10 \times 10^5$      | 5.3                       | $-17.44$         | 73                            | 0.29                          |
| m25a    | 10                            | $3.10 \times 10^5$      | 5.2                       | $-17.42$         | 78                            | 0.39                          |
| m15a2   | 20                            | $8.47 \times 10^4$      | 5.6                       | $-17.74$         | 79                            | 0.26                          |
| m15b    | 10                            | $9.23 \times 10^3$      | $-17.74$                  | Not applicable    | Not applicable                | Not applicable                |
| m15z    | 10                            | $2.62 \times 10^3$      | $-17.74$                  | Not applicable    | Not applicable                | Not applicable                |

Figure 5. Structure of the 15 M$_{\odot}$, Z = 0.02 model with a final kinetic energy of 10^51 erg (model m15a) 15.4 h after the explosion. Integrated mass $M(r)$ (solid) and $T(r)$ (dotted) are given in the left-hand plot, $\rho(r)$ (solid) and $v(r)$ (dotted) are given in the right-hand plot.

Figure 6. Same as in Fig. 5 but 34.3 h after the explosion, just after shock breakout.

Figure 7. Same as in Fig. 5 but 98 h after the explosion when the expansion of the envelope is almost homologous.

outward and deposits energy in the form of thermal energy. Weaker, reversed fronts are created at the chemical boundaries. For m15a, after approximately 1.5 d, the shock front reaches the outer stellar layers. The shock front is accelerated because of the steep density profiles at the surface layers of the star (Fig. 3), and produces a rapidly expanding outward layer (see Fig. 6, right-hand panel). During the following time, most of the thermal energy is used to overcome its potential, to do expansion work and to accelerate the expanding envelope. After approximately three to four sound crossing times of the progenitor, the expansion of the envelope is almost homologous, i.e. $v \propto r$, ending the phase dominated by hydrodynamics (see Fig. 7, right-hand panel). Subsequent energy release by radioactive decays causes only minor modifications of the density profile. In reality, some interaction with the surrounding medium may become important.

All models show a behaviour that is very similar to our example with some quantitative differences. For example, in the case of the explosion of a compact BSG, the shock front reaches the surface after approximately 1 h and the breakout temperatures are significantly higher, and subsequently, adiabatic cooling increases drastically (see Table 2 and Fig. 8).

The times until the shock breakout $t_{\text{shock}}$ (Table 2) are consistent with the analytical approximation by Shigeyama, Nomoto & Hashimoto (1988), who found that $t_{\text{shock}}$ scales with the stellar radius, and with the square of the mass and explosion energy. In our models, typical times are of the order of days for RSGs (1–3 d) and hours for BSGs (1–3 h).

It is worth noting that peak temperatures for RSGs are rather low, whereas BSGs can reach peak temperatures in excess of 10^6 K (see Table 2). The possible consequences for the production of high-energy photons at large redshifts are noted and the implications for the environment are discussed in Section 4.

Density structures and density gradients are given in Figs 9 and 10, respectively. As can be expected from the discussion of the stellar profiles (Fig. 3), the final density structures are rather similar for the RSGs. For BSGs, the density profiles are significantly steeper in the inner layers of the hydrogen-rich envelope which, as we will see, has strong effects on the LCs.

3.3 Light curves

In this section, we discuss the phase in which the properties of the envelope are mainly determined by free expansion and radiative processes and energy release is governed by stored energy, thermal energy, recombination processes and radioactive decay.

In general, an early maximum is seen, produced by the release of the stored thermal energy, followed by a plateau phase due to the recombinantion of H and, finally, a long tail due to the energy release by radioactive decay of $^{56}$Co (e.g. Fig. 11).

The last three columns of Table 2 show some properties of the LCs: the maximum visual magnitude (column 5), the length of the plateau phase, in days (column 6) and the size of the bump, in
magnitudes, occurring at the end of the plateau phase (column 7). The length of the plateau is defined by the times when \( M_V \) becomes smaller and larger than \( M_V(\text{max}) + 0.6 \) mag.

First, we consider the evolution of the structure for our reference model m15a, and the corresponding LCs (Figs 11–13). The initial flash in the light curve is due to the energy deposition at shock breakout. Its duration is of the order of the sum of cooling time, the light crossing time of the stellar radius and the shock travelling time through the photosphere. For RSGs, it is of the order of a few hours and for our BSGs approximately 10 min. For approximately 3 weeks after the explosion, the photospheric temperature is sufficiently high to maintain ionization up to the outer layers (Fig. 12). The opacity is dominated by Thompson scattering, bound–free and free–free processes in the optical and infrared (IR), and by line blocking in the ultraviolet (UV), resulting in very high optical depths of the envelope. Consequently, the expansion of the photosphere is strongly coupled to the expansion of the material.

The diffusion time-scales for photons, \( t_{\text{diff}} \), are given by

\[
t_{\text{diff}}(r) \approx \tau(r) r^2 / c,
\]

where \( \tau \) is the optical depth, \( r \) is the radius and \( c \) is the speed of light. In our example, at day 20, the diffusion time-scales exceed the expansion time-scales in all layers up to approximately an optical depth of 10. Consequently, the luminosity as a function of depth is not constant but increases inward due to the stored energy released by the shock front and the receding (in mass) photosphere (Fig. 12). For the same reason, models with low explosion energies show a brightening between 30 and 50 d after the explosion.

After the initial rise, the reference model shows an early plateau not seen in observations. This is caused by the 1D nature of the model or, more precisely, due to the assumption that Ni is not mixed. For models with moderate explosion energies, the diffusion timescales for energy stored by radioactive decays are longer than the expansion time-scale. Consequently, the luminosity is solely provided by the thermal energy stored during the explosion because the contribution from radioactive decay is delayed. This effect is well known from models for SN 1987A, where mixing had to be assumed to avoid this artefact and to obtain good fits to the LCs observed (e.g. Woosley, Pinto & Weaver 1988). Note that we do not see this early plateau in any observation. This may be a hint that the explosion mechanism is intrinsically aspherical and that mixing of the central layers is common in core collapse supernovae (see the introduction).

With time, the photospheric temperature drops, and recombination of H sets in. As a result of the strong drop in opacity with decreasing ionization, the position of the photosphere becomes almost stationary (Fig. 14). In Fig. 13, the structure of m15a is given at day 70, which is typical for the recombination phase. Diffusion time-scales for the envelope become comparable to the expansion time-scales. The luminosity is governed by the release of recombination energy, which is deposited just below the photosphere. Typically, the ionization degree at the photosphere drops to 1 per cent. Therefore, the luminosity as a function of radius increases outward up to the photospheric radius and stays constant for the outer layers. The rate of energy release depends on the recombination rate (in mass) and this depends on the mass flow through the photosphere,
energies, $10^{51}$ erg and $2 \times 10^{52}$ erg, models m15a and m15a2 in Table 2, respectively. The monochromatic LCs in $V$ and $B$ (upper panel) are given by the thick and thin lines, respectively. The luminosity is shown in the lower panel.

Figure 12. Luminosity, temperature, opacity and optical depth for the 15 $M_{\odot}$, $Z = 0.02$ model (m15a) before the recombination phase, at day 20.

Figure 13. Same as in Fig. 12 but during the recombination phase, at day 71.

i.e. on the density slope $n (\rho \propto r^{-n})$. Since the density of the envelope is rather flat and slowly changing, a self-regulating mechanism between energy release and heating of the photospheric region leads to an almost constant luminosity of the light curve. An increase in the energy release causes heating of the photosphere and, thus, a higher degree of ionization and greater opacity which, in turn, reduces the luminosity, and vice versa.

Eventually, the recombination front reaches the hydrogen-poor layers, and enters the He core. At this point, the photosphere recedes very quickly, causing an energy release and a small bump in the light curve at the end of the recombination/plateau phase (see Fig. 11 and below). Thereafter, the energy is purely determined by the instantaneous energy input due to radioactive decays, mainly by $^{56}$Co, up to a few hundred days after the explosion and then diffusion timescales become negligible. Except for models with extensive mixing of $^{56}$Ni, the envelope above the radioactive elements remains optically thick for $\gamma$-rays and the high-energy photons thermalize within the envelope almost completely.

At the onset of the recombination phase, $B - V$ increases rapidly due to the drop in temperature and the increasingly strong line blocking. Subsequently, during the recombination phase, $B - V$ changes slowly from approximately 1.2 to 1.5 mag because the conditions remain similar at the photosphere. At the end of the recombination phase, again, $B - V$ increases rapidly to approximately 2 mag due to the strong line blocking in the $B$ band, and due to a further decrease in temperature.

At the end of the plateau phase, the reference model shows a brief period of increasing brightness in $B$ and $V$, and bluer colours. This is caused by the rapid change in the He abundance at the photosphere, which results in an increased recombination temperature and a more rapidly decreasing photosphere and, thus, a temporary increase in the release of stored energy. These effects should be strong in SNe with a low explosion energy. Both the late increase brightness and the decrease in $B - V$ have yet to be observed. The lack of evidence for these effects may be regarded as a further indication that, in reality, the inner layers of SNe are strongly mixed during the explosion.

The influence of the kinetic energy on the light-curve shapes is shown in Fig. 11. Increasing the kinetic energy by a factor of 2 results in a faster rise of the light curve, an increased luminosity at the plateau ($\approx 0.27$ mag in the $V$ band), and a slightly bluer colour during the plateau phase. The overall similarities at the plateau are due to the similar density structures, as seen in the previous section (see Figs 9 and 10). The increase of $E_{\text{kin}}$ results in a faster expansion rate of the material (approximately 40 per cent) and increased energy deposition due to the shock front. As a result of the faster geometrical dilution, the stored thermal energy is released faster, causing an increase in the early luminosity. During the early recombination phase, thermal energy still contributes to the flux. The increased mass flux through the photosphere increases the luminosity by approximately 30–40 per cent according to the increase in the expansion velocity. The higher flux results in a slightly bluer colour of the more energetic model. In both models, we assume the same $^{56}$Ni ejection and, consequently, the LCs become very similar after day 130 and the luminosities of the light-curve tails are identical. However, the lower density requires a slightly higher colour for the more energetic model to maintain the same integrated emissivity.

Fig. 15 shows the LCs for our set of models with $Z = 0.02$ and different initial masses: 13, 15, 20 and 25 $M_{\odot}$, all of which explode as RSGs. The maximum brightness and the overall shape of the LCs remain very similar, showing a long plateau phase, in excess
Theoretical light curves of Type II-P SNe

Figure 14. Photospheric radius as a function of time for models with the same metallicity, Z = 0.02, but with different initial masses: 13 M⊙ (dotted), 15 M⊙ (solid), 20 M⊙ (dashed) and 25 M⊙ (long-dashed) on the left-hand panel and for models with the same mass, 15 M⊙, but different metallicities and/or kinetic energies on the right-hand panel: Z = 0.02 and 1 foe (solid), Z = 0.02 and 2 foe (dashed) and Z = 0 and 1 foe (dotted) on the right-hand panel.

Figure 15. Light curves for models with the same composition (Z = 0.02) and final kinetic energy (10^51 erg) but different initial masses: 13 M⊙ (m13a), 15 M⊙ (m15a), 20 M⊙ (m15a) and 25 M⊙ (M25a). The monochromatic LCs in V and B are given by the thick and thin lines, respectively.

of 50–60 d and extending up to 80–130 d from the explosion time. We identify this group as a homogeneous subclass among Type II-P, i.e. extreme SN II-P. The mean brightness in V during the plateau (≈ −17.4) is rather insensitive to the mass of the progenitor (ΔM_V ≤ 0.07 mag), and to the explosion energy if changed within a factor of 2. This subclass, extreme SN II-P, may be used as quasi-standard candle with few free parameters, namely the Ni mass.

The similarity of the light-curve shapes can be understood as a consequence of the similarity of the density slopes n (Fig. 10), which results in comparable energy production rates due to recombination. The main difference between the LCs is the length of the plateau phase, because of the increase in the total hydrogen mass that is available as a reservoir for storing ionization energy (see Table 2).

Compared with Litvinova & Nadézhin (1983, 1985), our RSG models show a similar correlation between the brightness during the mid-plateau stage and the kinetic energy, but a much weaker relation to the envelope mass. We have used relations (4) and (5) from Litvinova & Nadézhin (1985) to compute the mean V magnitude during the plateau and its duration as a function of explosion energy, progenitor radius and envelope mass. In contrast with our models, the mean V magnitude decreases up to 0.23 mag with mass (our mass range corresponds to envelope masses of between 11.6 and 23.6 M⊙) compared with a variation of 0.07 mag resulting from our models; the duration of the plateau phase increases with mass, as expected but, for all cases, is approximately 20–50 per cent longer than in our models. These discrepancies can be understood as a consequence of the progenitor structure (see the introduction). Litvinova & Nadézhin (1983, 1985) use parametrized density structures with the stellar radius as a free parameter, whereas our models are based on stellar evolution. In particular, Litvinova & Nadézhin (1985) change the envelope mass from 16 to 1 M⊙, but assume the same radius. Consequently, the column densities of the envelope differ by a factor of 16 and, consequently, so does the speed of the energy release. In contrast, our models m20a and m15a have an envelope mass of 18.6 and 13.6 M⊙, but the radius decreases from 970 to 670 R⊙ and the column densities in the envelope at a given radius are fairly similar.

For a BSG, i.e. m15z, the density slopes are much steeper compared with our reference model m15a (Fig. 10). Starting from a more compact envelope, the cooling by adiabatic expansion increases, while the overall luminosity decreases by more than a magnitude. The maximum V magnitude at the plateau phase increases by 1.3 mag (Table 2). In this case the LCs do not show the long plateau

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The explosion energy may be constrained by spectral observations.
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We find the following main results within the parameter space considered. For high metallicities, the stars explode as RSG regardless of the initial mass, showing a long plateau phase, greater than 50–60 d and extending to 80–130 d after the explosion (extreme SNe II-P). They can be understood as explosions of RSGs that have undergone rather moderate mass loss during the pre-supernova evolution. The V brightness during the plateau phase changes by approximately 0.2–0.7 mag. The mean absolute brightness in V (≈ 17.5 mag) during the plateau phase is rather insensitive to the mass of the progenitor and the explosion energy (within ≈ 0.3 mag). Note that line blocking in B and, in particular, in the UV depends on the metallicity, causing a somewhat larger spread.

The overall similarity of the LCs is caused by the similarity of the density structures of the red giant envelopes, and by the self-regulating propagation of the recombination front that determines the brightness during the plateau phase. For explosion energies smaller than $10^{51}$ erg, the self-regulating mechanism between photospheric radius and the location of the recombination front breaks down because the mean temperature of the envelope drops below the recombination temperature. Consequently, the absolute brightness during the plateau should drop fast with $E_{\text{kin}}$.

The metallicity plays a major role in determining the radius of the star because it affects the opacity, which directly determines the super-adiabatic gradient that holds in the more external layers. The greater the opacity, the larger the super-adiabatic gradient and hence the larger the radius of the star. This explains why, for low metallicities, stars explode as BSGs. The steep density profile results in a long lasting phase of increasing photospheric radius and brightness. The maximum brightness is lower by approximately 1.5 mag compared with the explosion of an RSG because of the increased expansion work for BSGs. Qualitatively, this tendency is consistent with SN 1987A. However, as shown above, a 13-M$_{\odot}$ star explodes as an RSG even for Z as low as $10^{-3}$.

The mass dependence of the final outcome has two main consequences. First, the discovery probability for SNe II at high z will decrease with the progenitor mass. The supernovae statistics will be systematically biased, starting at $z \approx 1$. The consequences for the study of the chemical evolution and the element production at high redshifts (e.g. by NGST) should be noted. Secondly, even at high redshifts, some extreme SNe II-P would be visible. Taking into account their unique properties, they may prove to be the key for the use of SN for cosmology at high z before SNe Ia occur. It is worth noting that the photospheric temperatures at the shock breakout are higher than in the solar metallicity models. As the cross-section for H-pho-toionization decreases with increasing frequency, $\sigma_{\nu} \propto \nu^{-3}$, the ionized circumstellar region around these SNe would be larger than in the RSG case. The possible consequences for the re-ionization in the early Universe may be noted.

Our results may suggest the use of a subclass of SNe II, the extreme SNe II-P, as quasi-standard candles. Although the use of extreme SNe II-P will not achieve the same accuracy as Type Ia supernovae, there are some distinct advantages. (i) Due to their unique LCs and colours, no spectrum is required for identification. (ii) The requirements on the time coverage of the LCs are very moderate: three or four deep images with a sample rate of 50–60 d in the rest frame will allow their discovery, identification and use for cosmology. At some time, two colour images should be taken to deselect flare stars and to handle the reddening. (iii) Finally, there is no need to follow the LCs after the plateau toward dimmer magnitudes. For the use of SNe Ia, the requirement to obtain a spectrum limits their use to $\approx 24$ mag if 8-m class telescopes are employed. For extreme SN II-P, (i)–(iii) imply that the largest ground-based telescopes with...
IR detectors can be used as search instruments, which pushes the limit to approximately 27–28 mag. Therefore, extreme SNe II-P may be used up to $z \approx 3$ using 8-m class telescopes. SIRTF may push the limit by another magnitude by long time exposures. Our results may be interesting with respect to the use of supernovae as distance indicators, and the supernovae statistics that may be constructed based on future observations by upcoming instruments such as NGST, SNAP and the like. For moderate to high metallicities, extreme SNe II-P may be used as standard candles with an accuracy of approximately 30 per cent if, in addition, the colour information is taken into account. Though not comparable with SNe Ia at low redshifts, their use may provide a valuable tool to supplement SNe Ia distances in our local Universe.

At moderate redshifts (e.g. $z = 3–3.5$), intergalactic metals have been discovered in the Lyα forest clouds showing metal abundances of $10^{-2}–10^{-3} Z_\odot$ (Songaila 1997; Cowie & Songaila 1998; Ellison et al. 2000), so it will still be possible to find extreme SNe II-P as distance indicators.

We also stress the limits of our investigations, which require further studies. For our purposes, we have explored a limited range of parameters. Recent observations show a wide range of explosion energies and Ni masses well beyond the ‘classical’ estimates of 1 and 2 foe and $0.07 M_\odot$ of Ni.

Hamuy (2002) found Ni masses of between 0.0016 to 0.26 $M_\odot$, and kinetic energies from $0.6 \times 10^{51}$ to $5 \times 10^{52}$ erg for envelope masses between 14 and 56 $M_\odot$. Hamuy’s interpretation for the kinetic energy and progenitor mass is based on extrapolation of the empirical relations by Litvinova & Nadézhin (1983, 1985), which have been obtained for envelope masses of between 1 and 16 $M_\odot$ and on parametrized structures (see also Section 3.3). Thus, the masses and explosion energies may be very uncertain. The importance of the progenitor structure also becomes evident in a direct comparison between the estimated progenitor mass of SNe II-P based on LCs and non-detections of progenitors. Based on SNe observations and on hydrodynamical models (Litvinova & Nadézhin 1983; Litvinova & Nadézhin 1985), Hamuy obtained progenitor masses of $43(+24/-14) M_\odot$ and $27(+14/-18) M_\odot$ for SN 1999gi and 1999em, respectively. From the length of the plateau phase for Sn 1999em, Höflich et al. (2000) found models with 15 $M_\odot$ to be consistent with observations. Based on non-detection of the progenitor on archive images and stellar evolution, Smartt et al. (2001) and Smarrt, Gilmore & Hodgkin (2002) found upper mass limits of 9(3/-2) and 12 $M_\odot$ for Sn 1999gi and Sn 1999em, respectively. However, despite the problems, Hamuy’s estimates of the total amount of $56$ Ni are hardly affected by the model assumptions.

A significant change in Ni will change the absolute brightness because radioactive decay contributes to the thermal reservoir feeding the LCs.

As discussed in Section 3.3, mixing of the central layers will change the early rise and the late plateau phases. Such a mixing must be expected from explosion models and should be included to improve the accuracy of the models.

No mass loss has been taken into account. Therefore, these models must be considered as extreme cases, severely limiting their use for the analysis of observations. In particular, strong mass loss by RSGs will affect the relation between the envelope mass and the stellar radius differently from the change in the initial mass, which determines the structure of the stellar core. This will probably increase the spread in parameter space. One further potential pitfall is the anisotropic luminosity caused by aspherical explosions of core collapse SNe. In general, the light of core collapse supernovae is polarized by $0.5 \pm 1$ per cent (e.g. Leonard et al. 2001, 2002; Wang et al. 2001). Polarization of this degree corresponds to asymmetries in the envelope that produce directional dependence in the observed luminosity of $0.3–0.6$ mag (Höflich 1991). However, extended H-rich envelopes tend to spherize the H-rich layers of the envelopes even if the explosions are assumed to be jet-like (Höflich et al. 2001). This tendency is consistent with recent observations for Sn 1999em.

In summary, the typical LCs and colours of our extreme SN II-P models are, at first order, in agreement with observations but a quantitative comparison and statistical analyses with observations must be postponed until complete data sets become available and the model grid has been extended. If performed, such a comparison may be used to obtain insights into details of the physics, such as fallback during the explosion, realistic predictions for the nucleosynthesis and constraints for core collapse models. For the application to cosmology and to control the interstellar reddening, the colour information must be considered and spectral information may be used to increase the accuracy. Taking current initiatives, e.g. CSP (Carnegie Supernova Program), LOTOSS (Lick Observatory and Tenagra Observatory Supernova Searches), NEAT (Near-Earth Asteroid Tracking), SDSS (Sloan Digital Sky Survey) and the upcoming SNAP and NGST missions, we expect an increasing availability of high-quality data.

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