Rapidly fading supernovae from massive star explosions

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ABSTRACT

Transient surveys have recently discovered a class of supernovae (SNe) with extremely rapidly declining light curves. These events are also often relatively faint, especially compared to Type Ia SNe. The common explanation for these events involves a weak explosion, producing a radioactive outflow with small ejected mass and kinetic energy ($M \sim 0.1 \, M_\odot$ and $E \sim 0.1 \, B$, respectively), perhaps from the detonation of a helium shell on a white dwarf. We argue, in contrast, that these events may be Type Ib/c SNe with typical masses and energies ($M \sim 3 \, M_\odot$, $E \sim 1 \, B$), but which ejected very little radioactive material. In our picture, the light curve is powered by the diffusion of thermal energy deposited by the explosion shock wave, and the rapid evolution is due to recombination, which reduces the opacity and results in an ‘oxygen-plateau’ light curve. Using a radiative transfer code and simple 1D ejecta profiles, we generate synthetic spectra and light curves and demonstrate that this model can reasonably fit the observations of one event, SN 2010X. Similar models may explain the features of other rapidly evolving SNe such as SN 2002bj and SN 2005ek. SNe such as these may require stripped-envelope progenitors with rather large radii ($R \sim 20 \, R_\odot$), which may originate from a mass-loss episode occurring just prior to explosion.


1 INTRODUCTION

As more powerful wide-field optical surveys come online, not only have the rates of supernova (SN) discoveries increased, but also has our ability to detect rarer events at greater distances and with lower luminosities. Of particular interest is a small but growing collection of unusual SNe whose light curves are relatively dim and of short duration. These rapidly fading supernovae (RFSNe) not only have peculiar light curves, but their spectra are also often distinctive, in some cases containing line features that have not yet been securely identified. Presumably, these transients have something interesting to tell us about the life and death of stars, but we still do not have a complete understanding of their physical properties or origins.

The class of RFSNe is diverse and may be broken up into several subclasses. In this paper, we focus on SN 2010X (Kasliwal et al. 2010) and similar events, which have been found in spiral galaxies and so could potentially be related to massive star death. The peak absolute magnitude of SN 2010X was \(-17\) (corresponding to a luminosity of \(\sim 10^{42} \, \text{erg} \, \text{s}^{-1}\)) and the light curve declined very rapidly after peak (by \(0.23 \pm 0.01 \, \text{mag} \, \text{d}^{-1}\)). The spectra showed line features of oxygen, calcium, and iron, with some uncertain features attributed to perhaps aluminium or helium. The light curve of a seemingly related event, SN 2002bj (Poznanski et al. 2010), was about \(2\) mag brighter than SN 2010X but declined at a nearly equal rate. The spectra of SN 2002bj contained features of silicon, sulphur and what was tentatively identified as vanadium. In both cases, the typical ejecta velocities, measured from the blueshift of the absorption lines, were around \(3000–10000 \, \text{km} \, \text{s}^{-1}\). Recently Drout et al. (2013) presented detailed observations of SN 2005ek, which strongly resembles SN 2010X in many ways.

Other RFSNe likely belong to distinct subclasses. Events like SN 2005E have been labelled ‘calcium-rich transients’ (Kawabata et al. 2010; Perets et al. 2010; Kasliwal et al. 2012), as their late-time spectra are dominated by calcium emission. These SNe have been found in the outskirts of elliptical galaxies with no signs of star formation and therefore likely originate from old stellar populations. Another class of RFSNe, the ‘SN 2002-ex-like’ or ‘Iax’ events, show some spectroscopical similarities to Type Ia supernovae (SNe Ia), but are distinguished by low peak magnitudes (between about \(-14\) and \(-19\) in the \(V\) band) and low ejecta velocities (Foley et al. 2013).

Several physical models have been proposed to explain the RFSNe. In almost all cases, the rapid evolution of the light curves is explained as a consequence of a low ejected mass (\(<0.1 \, M_\odot\)), resulting in a short photon diffusion time through the ejecta. The ‘Ia’ model, for example, considers the detonation of a thin shell of
helium that has accreted on to the surface of a carbon/oxygen (C/O) white dwarf (Bildsten et al. 2007; Shen et al. 2010). The model is so named because the kinetic energy (\(\sim 0.1 \, \text{B} \), where \(1 \, \text{B} = 10^{51} \text{erg}\)) as well as the ejected mass and luminosity are each about a tenth of those of a typical SN Ia. This model can reproduce some basic properties of the SN 2010X light curves (Kasliwal et al. 2010). However, as we discuss later, the model has difficulty reproducing important features of the observed spectra and the shape of the light curve. In addition, current ‘Ia’ models do not reach the higher luminosities seen in events like SN 2002bj.

Partial explosions of C/O white dwarfs near the Chandrasekhar mass have also been suggested as an origin of RFSNe. Kromer et al. (2013) simulate a centrally ignited deflagration that burns a portion of the star but does not release enough nuclear energy to completely unbind it. Instead, a fraction of the mass (\(\sim 0.4 \, \text{M}_\odot\)) is ejected with low kinetic energy and an \(56\text{Ni}\) content of \(\sim 0.1 \, \text{M}_\odot\). The resulting transients are dim but have fairly long diffusion times due to the relatively high amount of ejected matter and low energy. The light curves therefore do not decline rapidly enough to match the SN 2010X-like events, although this model may explain the SN 2002cx-like transients.

Another potentially relevant model is the accretion-induced collapse (AIC) of a white dwarf to a neutron star. In the AIC simulations of Dessart et al. (2006), only a very small amount of radioactive material (\(\sim 10^{-4} - 10^{-3} \, \text{M}_\odot\)) is ejected. The resulting transient should therefore be very dim. The simulations of Fryer et al. (2009), however, find larger radioactive masses (\(\sim 0.05 \, \text{M}_\odot\)) and predict brighter SNe. For rapidly differentially rotating white dwarfs, a centrifugally supported disc may form during collapse and subsequently be blown apart, perhaps synthesizing even more \(56\text{Ni}\) (Metzger, Piro & Quataert 2009; Abdikamalov et al. 2010; Darbha et al. 2010). In these models, the ejecta velocities are fairly large, near the escape velocity of the neutron star (\(\sim 0.1 - 0.3c\)). If the WD is surrounded by a relatively dense circumstellar medium, the ejecta may be slowed down and the light curves powered in part by shock heating (Fryer et al. 2009; Metzger et al. 2009).

While the above white dwarf models may explain a subset of the observational class of RFSNe, in this paper, we argue that they cannot explain all such events. We consider in particular the SN 2010X-like transients and highlight two observables that may point to a different origin. The first is the precipitous decline in the post-maximum light curve with no sign, at least within the limits of the observations, of a radioactively powered light curve tail at late times. This suggests that the amount of radioisotopes ejected is quite small. The second is the presence of certain strong spectral features, in particular OI. In this paper, we show that the OI lines in SN 2010X may require a relatively large mass of ejected oxygen, which is difficult to accommodate along with the rapid decline in brightness in a ‘Ia’ or similar model. A similar estimate of the oxygen mass is discussed by Drout et al. (2013) in an analysis of SN 2005ek.

Some previous studies have considered a core-collapse explanation for RFSNe. Moriyi et al. (2010) simulate low-energy explosions in massive stars and show that, with proper tuning, only a small amount of mass may be ejected (\(\sim 0.1 \, \text{M}_\odot\)) with most of the star falling back on to a compact remnant (a black hole). The 1D models of Moriyi et al. (2010) assume an artificial complete mixing, although the authors speculate that a jet-powered explosion may be able to carry \(56\text{Ni}\) to the surface layers. Drout et al. (2013) also discuss the possibility of a low-energy (0.25–0.52 B) core-collapse explanation for SN 2005ek with an inferred ejecta mass of 0.3–0.7 M\(_\odot\), an \(56\text{Ni}\) mass of 0.03 M\(_\odot\), citing fallback among a few explanations for such a low-mass ejection. One question this raises is how the radioactive \(56\text{Ni}\), which is usually produced in the dense innermost regions of the star, avoids falling back and instead is ejected with the outer layers of the star.

The common feature of all of the above models has been an unusually low ejected mass and energy. Here, in contrast, we show that the mass and energy of SN 2010X-like events may be typical of SNe Ib/c (\(M \sim 1–5 \, \text{M}_\odot\), \(E \sim 1 \, \text{B}\)). We attribute the luminosity not to radioactivity but to the thermal energy deposited by the explosion itself. The rapid light curve decline, despite the relatively high ejected mass, can be explained by recombination, which dramatically reduces the effective opacity.

The possibility that some SNe may fail to eject radioactive isotopes has been considered before. Fryer et al. (2009) discuss models of very massive stars (\(\geq 20 \, \text{M}_\odot\)) in which the amount of material that falls back on to the remnant may be quite substantial, i.e. several solar masses. Essentially all of the \(56\text{Ni}\) is formed in the innermost layers of the ejecta and falls back, robbing the light curves of energy from radioactive decay and producing very dim events (\(V\) and \(B\) magnitudes of \(-13\) to \(-15\)). Ugliano et al. (2012) indicate that such a large amount of fallback material is unlikely, probably not more than \(\sim 0.2 \, \text{M}_\odot\), but this may still be enough to accrete more if not all of the radioactive material produced. Dessart et al. (2011) have considered Type Ib models that lack \(56\text{Ni}\) and shown that they produce relatively short duration, thermally powered light curves with peak luminosities (\(\sim 10^{40} - 10^{41} \, \text{erg s}^{-1}\)).

In this paper, we explore such models of massive star explosions as an explanation for SN 2010X-like events. We first argue that SN 2010X ejected a substantial amount of oxygen, suggestive of the explosion of a stripped-envelope, massive star (Section 2). We then demonstrate that massive SNe can produce brief, rapidly declining light curves once recombination is taken into account (Section 3). We then use the radiative transfer code Sedona (Kasen, Thomas & Nugent 2006) to produce synthetic light curves and spectra of simple, 1D ejecta models, and show that these models can reproduce the SN 2010X light curve, provided that the progenitor star had a large enough radius (Section 4). In Section 5, we discuss various progenitor scenarios that may be responsible for this class of SNe.

### 2 ESTIMATES OF THE EJECTA MASS

Analytical scaling relations are commonly used to estimate the ejecta mass and kinetic energy of observed SNe. For ejecta of mass \(M_{\text{ej}}\) and velocity \(v\), and assuming a constant opacity \(\kappa\), the duration of the light curve \(t_{\text{sn}}\) is set by the effective diffusion time through the expanding ejecta (Arnett 1979):

\[
t_{\text{sn}} \approx 34 \left( \frac{M_{\text{ej}}}{\text{M}_\odot} \right)^{1/2} \kappa_{0.1}^{1/2} v_{1}^{-1/2} d, \tag{1}
\]

where \(v_{1} = v/10^{5} \text{km s}^{-1}\) and \(\kappa_{0.1} = \kappa/0.1 \text{cm}^{2} \text{g}^{-1}\). We have calibrated the numerical constant based on SNe Ia, which have \(v_{1} \approx 1\), \(M_{\text{ej}} \approx 1.4 \, \text{M}_\odot\) and a bolometric light curve width (i.e. rise plus fall) of roughly 40 d (Contardo, Leibundgut & Vacca 2000). The value \(\kappa = 0.1 \text{ cm}^{2} \text{g}^{-1}\) is appropriate for electron scattering in singly ionized helium. It is also similar to the mean opacity due to Doppler broadened lines of iron-group elements, which is the dominant form of opacity in SNe Ia (Pinto & Eastman 2000).

Inverting equation (1) for the ejecta mass gives

\[
M_{\text{ej}} \approx 0.0875 \left( \frac{t_{\text{sn}}}{10 \text{d}} \right)^{2} v_{1} \kappa_{0.1}^{-1} \text{M}_\odot, \tag{2}
\]

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which has fostered the belief that RFSNe like SN 2010X represent relatively low-mass ejections. Such an argument, however, presumes a constant opacity of $\kappa \sim 0.1 \text{cm}^2 \text{g}^{-1}$. In fact, the opacity of SN ejecta is highly dependent on the physical state and, as we discuss in the next section, may vary by an order of magnitude depending on the temperature and composition of the ejecta.

It is possible to derive an independent constraint on the ejecta mass using absorption features observed in the spectrum. In particular, SN 2010X showed a strong, broad and persistent O I triplet feature ($\lambda \lambda 7772, 7774, 7775$), which would seem to suggest a significant mass of oxygen. In homologously expanding atmospheres, the degree of absorption is quantified by the Sobolev optical depth,

$$\tau_{sob} = \left( \frac{\pi e^2}{m_e c^2} \right) t_{exp} \lambda_0 n_1,$$

where $\lambda_0$ is the rest wavelength of the line, $t_{exp}$ the time since explosion and $n_1$ the number density in the lower level of the atomic transition.

In Fig. 1, we plot contours of $\tau_{sob}$ for the O I triplet line as a function of density and temperature for ejecta composed of pure oxygen at $t_{exp} = 30$ d, a time when the oxygen absorption feature is quite prominent in SN 2010X. To estimate $n_1$, we have assumed that the ionization/excitation states were approximately given by local thermodynamic equilibrium (LTE). Fig. 1 shows that a density of at least $\rho_c \approx 10^{-14} \text{g cm}^{-3}$ is required to achieve strong ($\tau_{sob} \gtrsim 1$) absorption in the O I line. This critical density corresponds to the ideal temperature of $T \approx 5500 \text{K}$, at which the level density $n_1$ is highest. For hotter temperatures, oxygen becomes more highly ionized, while for cooler temperatures it is difficult to thermally populate the excited lower level of the O I transition. In these cases, an even higher density is required to make the line optically thick.

We can use this critical O I density to obtain an approximate lower limit on the total ejecta mass of SN 2010X. The February 23 spectrum (close to $t_{exp} \approx 20$ d) showed apparent O I absorption at velocities $\approx 10000 \text{km s}^{-1}$. Assuming that the ejecta density profile is the number density in the lower level of the atomic transition, we obtain a total ejecta mass of $\sim 2 M_\odot$, which is consistent with the values expected for SNe Ia. The O I feature of SN 2010X at a comparable epoch ($t_{exp} \approx 30$ d) is significantly broader and deeper than that of SN 1994D. We therefore consider it likely that the ejected mass of SN 2010X was comparable to or larger than that of a typical SNe Ia.

The association of SN 2010X with a massive progenitor is strengthened by comparison with core-collapse SNe. Fig. 2 shows the SN 2010X spectra with those of SN 1994D, which is considered a fairly typical, if somewhat fast-evolving, SNe Ic. The agreement is striking and strongly points to a similar physical origin for the two. Drout et al. (2013) have also noted the spectroscopic resemblance of SN 2005ek to other normal SNe Ic as well as SN 2010X. The light curve of SN 1994I showed a clear radioactive tail, indicating that it ejected $\sim 0.07 M_\odot$ of $^{56}$Ni (Iwamoto et al. 1994; Young, Baron & Branch 1995). We will suggest that SN 2010X was a compositionally similar SN Ib/c but did not eject as much $^{56}$Ni.

### 3 Oxygen-Plateau Supernovae

The mass estimates discussed in the last section present a paradox – the narrow light curve of SN 2010X suggests a low $M_{ej}$, while the spectroscopic constraints indicate that $M_{ej}$ may be many times larger. Here, we show that the conflicting estimates can be reconciled in a core-collapse model in which the ejecta mass is large ($M \gtrsim 1 M_\odot$) but where the effective diffusion time is significantly reduced due to recombination.

The opacity of SN ejecta is highly dependent on the ionization state and so may vary significantly with temperature. In Fig. 3, we plot the Rosseland mean opacity (calculated assuming LTE) of SN ejecta of different compositions. We consider in particular an oxygen–neon–magnesium composition (see Table 1) which may be characteristic of the massive, stripped-envelope stars believed to be the progenitors of SNe Ic. For higher temperatures ($T \gtrsim 6000 \text{K}$), the O–Ne–Mg opacity has a characteristic value $\kappa \approx 0.04 \text{cm}^2 \text{g}^{-1}$. When the temperature drops below 6000 K, however, oxygen recombines to neutral and the opacity drops sharply by more than an order of magnitude. This is because, in the absence of scattering off of free electrons, photons can escape through the “windows” in wavelength space that occur between the lines, reducing the

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**Figure 1.** Logarithmic Sobolev optical depth of the combined O I $\lambda\lambda 7772, 7774, 7775$ triplet line as a function of density and temperature for a 100 per cent oxygen composition at $t_{exp} = 30$ d. The black lines indicate curves of constant optical depth. The lowest point in the $\tau = 1$ curve occurs at $\rho_c \approx 10^{-14} \text{g cm}^{-3}$, which is taken to give the lowest possible density needed to see the O I absorption.
Figure 2. Comparison of the multi-epoch spectra of the SN Ic 1994I to those of SN 2010X. Times since $B$-band maximum are listed. The strong spectral similarity may indicate a similar physical origin.

Rosseland mean opacity. However, the opacity does not drop to zero at $T \lesssim 6000 \text{ K}$ because other elements (such as Mg and Si) with lower ionization potentials remain ionized. For a helium-rich composition, recombination occurs at a higher temperature ($\sim 10,000 \text{ K}$) due to the higher ionization potential of helium. In contrast, the opacity of $^{56}\text{Ni}$ and its daughter nuclei ($^{56}\text{Co}$ and $^{56}\text{Fe}$), due to the lower ionization potential of the iron group species, maintains a large value as long as $T \gtrsim 3000 \text{ K}$.

The recombination physics will strongly influence the light curves of SNe composed largely of oxygen. The radiative transfer parallels the well-understood effects in SNe IIP (e.g. Grassberg, Imshennik & Nadyozhin 1971; Dessart & Hillier 2008). Initially, the ejecta are heated and ionized by the passage of the explosion shockwave. As the ejecta expand and cool, however, the material eventually drops below the recombination temperature $T_i$ and becomes largely transparent. Because the outer layers of ejecta are the coolest, they recombine first, and a sharp ionization front develops in the ejecta. As time goes on, the ionization front recedes inwards in mass coordinates, releasing the stored thermal energy. When this recombination wave reaches the centre of the ejecta, the stored energy is exhausted and the light curve should drop off very rapidly, marking the end of the ‘oxygen-plateau’ phase. The analogous case of a helium plateau in SN Ib has been discussed by Ensmann & Woosley (1988) and Dessart et al. (2011).
where $E$ is the explosion energy, $M$ is the ejected mass, $\rho$ is the mass density, $r$ is the coordinate of the remnant, and $t$ is the time since the start of the calculation.

Relationships for the time-scale and peak luminosity of SNe II, including the effects of recombination, have been determined by Popov (1993) and verified numerically by Kasen & Woosley (2009), who find

$$t_{\text{sn}} \approx 120 E_{31}^{-1/6} M_{10}^{1/2} R_{500}^{1/4} T_{6000}^{-2/3} \text{ d},$$

$$L_{\text{sn}} \approx 1.2 \times 10^{42} E_{51}^{1/2} M_{10}^{-1/2} R_{500}^{3/4} T_{6000}^{-3/4} \text{ erg s}^{-1},$$

where $E_{31} = E / 10^{31}$ erg is the explosion energy, $M_{10} = M / (10 M_\odot)$ is the ejected mass, $R_{600} = R / (500 R_\odot)$ is the pre-SN radius, $R_{500} = R / (500 R_\odot)$ is the opacity of the ejecta and $T_{6000} = T / (6000 K)$ is the ejecta temperature. The numerical calculations of Kasen & Woosley (2009) actually found a scaling closer to $t_{\text{sn}} \propto E^{-1/4}$ rather than $E^{-1/6}$, but otherwise the relations are the same. We can use similar arguments for hydrogen-less SNe, assuming that the luminosity is determined by the recombination temperature of whatever species dominates the ejecta.

Inverting equations (4) and (5) allows us to solve for the ejecta mass and pre-SN radius in terms of observed quantities,

$$M_{\text{ej}} \approx 2.9 L_{42}^{-1/4} t_{20}^{-4} R_{500}^{1/4} T_{6000}^{-1} M_\odot,$$

$$R_{\odot} \approx 12.4 L_{42}^{2/5} v_{4}^{-2} R_{500}^{1/4} T_{6000}^{-1} R_\odot.$$  

These are very rough estimates, but they demonstrate that, when recombination is accounted for, the light curves of SN 2010X and other RFSNe are consistent with massive ($M_{\text{ej}} \gtrsim 1 M_\odot$) explosions which powered by shock energy, not radioactivity, provided that the radius of the progenitor star is sufficiently large.

4 RADIATIVE TRANSFER MODELS

To model the light curves and spectra of RFSNe in more detail, we use the time-dependent Monte Carlo radiative transfer code SEDONa (Kasen et al., 2006). We base our calculations on simple parametrized ejecta models rather than on detailed hydrodynamical simulations, as this allows us to easily control the ejecta mass, kinetic energy and progenitor star radius. We vary these parameters, in an empirical spirit, in an effort to fit the observations of SN 2010X and constrain its physical properties.

4.1 Ejecta models

For simplicity, we consider ejecta models that are spherically symmetric and in the homologous expansion phase. Simulations of core-collapse explosions suggest that the ejecta density structure can roughly be described by broken power-law profile (Chevalier 1992),

$$\rho_{\text{in}}(r, t) = \xi_0 M \frac{r}{v_t t}^{-\delta} \quad \text{for } v < v_t,$$

$$\rho_{\text{out}}(r, t) = \xi_0 M \frac{r}{v_t t}^{-\eta} \quad \text{for } v \geq v_t,$$

where $v_t$ is the velocity at the transition between the two regions, $\xi_0 = 4.5 \times 10^7 \xi_1 (E_{51} / M_\odot)^{1/2} \text{ cm s}^{-1}$.

The coefficients $\xi_0$ and $\xi_1$ are constants which can be determined by requiring equation (8) integrate to the specified mass and energy. In our model for SN 2010X, we use $\delta = 1$ and $\eta = 8$ as they are typical values for core-collapse SN and produce reasonable fits to the light curves and spectra. These are parameters that, along with $M_{\text{ej}}$, $E_{51}$ and $R_\odot$, are used to adjust the output light curves and spectra.

Immediately following the passage of a core-collapse SN shock-wave, the explosion energy is roughly equally split between the kinetic energy and thermal energy of the stellar material. The latter is strongly radiation dominated. Simulations suggest that, before radiative diffusion sets in, the ratio of the radiation energy density to the mass density is nearly constant throughout most of the envelope (Woosley 1988). We therefore take the energy density profile at $t_0$, the start time of our calculation, to be

$$\epsilon(v, t_0) = \frac{E_{51}}{2 M} \left( \frac{R_\odot}{R_{\text{ej}}} \right),$$

where $R_{\text{ej}} = v_t t_0$ is the size of the remnant at the start of our transport calculation. This expression assumes that the total thermal energy equals $E_{51}/2$ when $R_{\text{ej}} = R_\odot$; the term in parentheses accounts for losses due to adiabatic expansion prior to the start of our transport calculation. In this model, the initial energy density profile is a broken power law with the same exponents as the mass density. This is reasonably consistent with analytical results that find that the energy density power law in the outer layers is very similar to, though slightly steeper than, the mass density profile (Chevalier 1992).

We assume that the composition of the ejecta is homogenous in two layers. Detailed abundances are given in Table 1. Abundances for the inner layers ($v \leq 10^{10} \text{ km s}^{-1}$) are typical of O–Ne–Mg layers of a massive star and taken from the stellar evolution models of Woosley, Heger & Weaver (2002) for a 25 $M_\odot$ pre-SN star at a mass coordinate of 3.9 $M_\odot$. For the outer layers ($v > 10^{10} \text{ km s}^{-1}$), we assume He-rich material with solar abundances of metals. The inclusion of helium in the outer layers in fact does not significantly affect the light curves and spectra, as the photosphere at the epochs of interest turns out to be in the O–Ne–Mg layers. For the models in this paper, we assume that no radioactive isotopes were ejected, so the light curves are solely powered by the energy deposited in the explosion shock wave.

4.2 Synthetic light curves and spectra

We performed radiative transfer calculations for a series of models, in which we vary the three key ejecta parameters: the explosion $E$, the ejected mass $M_{\text{ej}}$ and the pre-SN radius $R_\odot$. Fig. 5 shows how the Sloan Digital Sky Survey (SDSS) $r$-band light curve changes as...
we vary each parameter while holding the others fixed. We show the $r$-band curves for easy comparison to SN 2010X, as this is the band in which we have the most data. The general trends are qualitatively consistent with the scaling relations (equations 4 and 5). Increasing the explosion energy shortens the light curve duration while increasing the peak luminosity. Raising the mass increases the light-curve duration but does not strongly affect its peak luminosity. Finally, a larger pre-SN radius increases both the luminosity and duration of the light curve. The light curves resemble those presented in Dessart et al. (2011) for models of SNe Ib/c assumed to eject no $^{56}$Ni (particularly models Bmi25mf6p49z1 and Bmi25mf7p3z0p2).

In Fig. 4, we show a fit to the light curve of SN 2010X, using a model with $M_0 = 3.5 M_\odot$, $E = 1 B$ and $R_0 = 2 \times 10^{12}$ cm. The model demonstrates that the basic properties of these RFSNe can be explained by the explosion of an ordinary-mass star in which the emission is powered solely by the energy deposited in the explosion shockwave, without any radioactive $^{56}$Ni. The assumed radius of the progenitor, however, is significantly larger than that of typical Wolf–Rayet (WR) stars, an issue we return to in Section 5. The short duration of the model light curve reflects the rapid release of radiation energy by the receding combination wave. The luminosity for the first 25 d (the ‘oxygen plateau’) is fairly constant but then drops dramatically as the combination wave nears the centre of the ejecta and the stored radiation energy is exhausted. After day 25, the $r$-band magnitude drops by more than 3 mag in only 5 d, marking the end of the plateau phase. As no radioisotopes were included, the light curve shows no radioactive tail at late times and the luminosity continues to drop rapidly.

The light-curve fit does not uniquely constrain all three model parameters ($M$, $E$ and $R_0$) as there are essentially only two photometric observables (light-curve brightness and duration). We have chosen to show here a model in which the mass and energy are typical of ordinary SNe Ic, but other combinations can provide fits of similar quality (see Fig. 5). The degeneracy can perhaps be broken by using the observed velocity to constrain the mass energy ratio; however, the photospheric velocity in plateau SNe is set by the location of the recombination front and hence is not necessarily indicative of $v \approx (2E/M)^{1/2}$.

Fig. 6 compares the synthetic spectrum (at $t_{\text{exp}} = 24$ d) of the same model to the February 23 spectrum of SN 2010X. On the whole, the model does a good job reproducing the major spectral features and in particular predicts significant absorption near the O i triplet. This supports the idea that the composition of the SN 2010X ejecta is consistent with that of an O–Ne–Mg core of a massive star. In detail, however, one notices discrepancies in the position and depth of several features. For instance, the model absorption near 5600 Å, due to the sodium Na i d line, is much too weak and has too low a velocity. A similar problem with the Na i d line has often been noted in models of SNe IIP and has been explained as resulting from the neglect of time-dependent non-LTE effects (Dessart & Hillier 2008). Thus, while fine-tuning of our ejecta parameters could likely improve the spectral fit, the overall agreement is presumably limited by the simplified nature of the calculations, including the one-dimensional broken power-law density structure, the two-zone uniform composition and the neglect of non-LTE effects.

The identification of the absorption features at 6800 and 7000 Å was the subject of some discussion in Kasliwal et al. (2010), who suggest that these features may be due either to lines of Al ii or He i. Our model does not include aluminium, and the helium lines are optically thin, given the lack of non-thermal excitation from radioactivity. Analysis of the Sobolev optical depths suggests that lines of Fe ii and neutral species (S ii $\lambda 7035$ and Ca i) contribute to the spectral features in this wavelength region. Drout et al. (2013) similarly show that the spectra of SN 2010X-like events can be reasonably fit without invoking aluminium or helium absorption lines.

In Fig. 7, we show the spectral time series of SN 2010X alongside select spectra from our model. The general trends are reasonable, but the colour evolution is faster in the model. For example, the day 10 model spectrum is bluer than the day 9 observed spectrum, while the day 31 model spectrum is redder than the observed day 36 spectrum. Our radiative transport becomes suspect at later times ($\gtrsim 30$ d) as the ejecta are becoming optically thin and non-LTE effects should become more significant. While the model spectral series does not reproduce every observed spectral feature, we emphasize that we have chosen to limit any fine-tuning of the abundances and explosion parameters in order to fit the data. Further adjustment of the oxygen-rich composition would presumably lead to an improved fit, as has been shown in the modelling of the spectroscopically similar SN 1994I (Sauer et al. 2006).

### Table 1. Mass fractions used for the composition in the radiative transport models. The boundary between inner and outer zones is at $10^9$ cm. For some isotopes in the inner layer, the abundance was increased to solar.

<table>
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<th>Species</th>
<th>Inner abundance$^a$</th>
<th>Outer abundance$^b$</th>
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<tbody>
<tr>
<td>H</td>
<td>1.3441e−14</td>
<td>–</td>
</tr>
<tr>
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$^b$Solar composition from Lodders (2003) with all hydrogen converted to helium.

5 DISCUSSION AND CONCLUSIONS

We have argued that some RFSNe, in particular the SN 2010X-like events, are the result of core-collapse explosion of massive stripped-envelope stars. This contradicts previous suggestions that these events represent low-mass, low-energy outbursts from, for example, ‘Ia’ explosions on white dwarfs. In our picture, the SN...
Figure 4. Light curves in g, r and i calculated for a pure explosion model of SN 2010X, plotted against the data. This model was obtained with $M_{ej} = 3.5 M_\odot$, $E_{51} = 1$ and $R_0 = 2 \times 10^{12}$ cm. The dashed lines show light curves in UBVRI for SN 1994I, a typical SN Ic, for comparison.

Figure 5. Calculated light curves using parameter variations around our fiducial ejecta model for SN 2010X, which has parameters $M_{ej} = 3.5 M_\odot$, $E_{51} = 1$ B and $R_0 = 2 \times 10^{12}$ cm. Top left: light curve calculations holding all parameters constant except ejecta mass. Top right: same as the top-left panel but with varying explosion energy. Bottom left: same as top-right and top-left panels but with varying pre-SN radius. Bottom right: an alternative model that fits the data fairly well with parameters $M_{ej} = 6 M_\odot$, $E_{51} = 3$ B and $R_0 = 9 \times 10^{11}$ cm. This demonstrates the degeneracy in our approach and that the light curves could be fitted with a range of parameters.
Figure 6. Selected spectrum calculated from our fiducial ejecta model of Fig. 4 shown against observed data. The overall shape is similar, and most of the important spectral features are reproduced. Discrepancies may arise from our assumption of LTE, simplified power-law density structure or the untuned abundances assumed.

Figure 7. Time series of selected synthetic spectra of our fiducial ejecta model of Fig. 4 compared the observed data of SN 2010X showing the evolution of the oxygen line and other prominent features. The order of the observed and synthetic spectra is chosen to highlight spectral similarities, some of which are more easily seen by comparison of spectra at slightly different phases.

ejected very little radioactive material and the light curve was instead powered by the diffusion of thermal energy deposited by the explosion shock wave. The short duration of the light curve, despite the relatively high ejected mass ($M \sim 3-4 M_\odot$), is due to recombination, which dramatically reduces the effective opacity. The evolution is similar to SNe IIP, and the sharp decline of the light curve can be understood as reflecting the end of an ‘oxygen plateau’. Our 1D radiation transport models demonstrate that the observations of SN 2010X are consistent with this scenario. Empirically, the spectral similarity of SN 2010X with the SN Ic 1994I strongly suggests that these events have oxygen-dominated ejecta as would be expected in stripped core-collapse SNe. Similar rapidly
declining plateau light curves could happen in carbon/oxygen-rich or helium-rich ejecta.

Other RFSNe may have a similar origin. The light curve of SN 2002bj had a very similar decline rate to that of SN 2010X, but the peak luminosity was about 2 mag brighter. The model scalings suggest that the brightness and duration could be reproduced in a SN Ib/c plateau with larger progenitor radius and/or higher explosion energy. The spectral features of SN 2002bj were distinct from SN 2010X, perhaps because the ejecta temperatures were higher, but possibly because the composition of the ejecta was different (e.g. helium rich instead of oxygen rich). Further modelling is needed to constrain the ejecta properties in detail.

Recently, Drout et al. (2013) presented a detailed analysis of SN 2005ek, which was spectroscopically and photometrically similar to SN 2010X. The late-time R- and I-band observations of SN 2005ek (at 40 and 70 d after peak) do perhaps indicate the presence of a radioactively powered light-curve tail. The uncertain bolometric corrections, however, make it difficult to determine the actual gamma-ray trapping rate and hence radioactive mass. The late-time light-curve decline is consistent with nearly complete gamma-ray trapping, as might be expected in a massive (M ~ 3 M☉) event. In this case, the inferred 56Ni mass, while not zero, is very small, Mni ≈ 1–4 × 10^-3 M☉. The luminosity at the light-curve peak would then be attributed to an oxygen plateau of the sort we have described.

In contrast, Drout et al. (2013) argue that if the ejecta mass and kinetic energy of SN 2005ek were relatively low (M ≈ 0.35–0.7 M☉, E ≈ 0.25–0.52 B), then most of the gamma-rays escape at late times and the inferred 56Ni mass is much larger, Mni ≈ 0.03 M☉, sufficient to power the light-curve peak. It is not clear, however, that such a model can explain the rapid light-curve decline after peak. Iwamoto et al. (1994) considered a similar model for SN 1994I with M ≈ 0.53 M☉, E ≈ 1 B and Mni ≈ 0.08 M☉, and found light curves which declined less rapidly and showed a clear radioactive tail. More recently, models were explored in a different context by Fink et al. (2013), who calculated radiative transport models for similar scenarios (e.g. model ND3 with M ≈ 0.2 M☉, E ≈ 0.43 B and Mni ≈ 0.07 M☉) and found light curves that decline fairly gradually, dropping by only ~1 mag in R band in 15 d after peak. This is much more gradual than either SN 2005ek or SN 2010X (which dropped ~3 R-band mag in 15 d). These results suggest that the radioactively powered model may struggle to explain the rapid decline that characterizes this class of RFSNe.

The light curve of SN 2002bj poses an even greater challenge for radioactively powered models. This event was significantly brighter than either SN 2005ek and SN 2010X, such that the inferred 56Ni mass would be Mni ≈ 0.15–0.25 M☉ (Poznanski et al. 2010). To be consistent with the rapid rise and steep decline of the light curve, one would need to assume a small ejecta mass, M ~ 0.3 M☉, such that the ejecta consisted of very little else but 56Ni. This, however, contradicts the observed spectrum, which did not show strong features from iron group elements.

A potentially revealing empirical discriminant of the RFSNe is the ratio of the luminosity measured at peak to that on the radioactive tail. Some events, like SN 2002cx, SN 2005E and SN 2008ha, show a moderate peak-to-tail ratio, similar to SNe Ia and consistent with a light curve powered entirely by radioactivity. In contrast, the events considered here (SN 2005ek, SN 2010X and SN 2002bj) show a larger peak-to-tail luminosity ratio (no tail at all) more reminiscent of SN IIP. It is possible that this distinction separates those events powered solely by radioactivity from those with an initial thermally powered oxygen (or helium) plateau.

The RFSNe also are distinguished by their host galaxies. All of SN 2010X, SN 2002bj and SN 2005ek were found in star-forming galaxies and so are consistent with young stellar populations and massive star progenitors. Other types of RFSNe, however, such as SN 2005E and similar low-luminosity calcium-rich transients have often been found in the remote outskirts of elliptical galaxies, which almost exclusively harbour old stars. For these events, a different model, perhaps based on white dwarf progenitors, may be appropriate.

If correct, the identification of SN 2010X-like events as oxygen-plateau SNe has two important implications for core-collapse SNe. The first is that some stripped-envelope SNe may eject a very small amount (≲10^-3 M☉) of radioactive isotopes. This may be because abundant radioactivity was not synthesized in the explosion or because the inner ejecta layers remained bound and fell back onto the compact remnant. The fallback process is not well understood; it has mostly been studied in parametrized 1D models with an artificial inner boundary condition (e.g. Zhang, Woosley & Heger 2008, but see Ugliano et al. 2012). Fallback is expected to be most significant in low-energy explosions, but it can also be substantial in more energetic SNe if a strong reverse shock propagates inwards and deCELERates the inner layers of ejecta (Chevalier 1989; Zhang et al. 2008; Dexter & Kasen 2013). If the progenitor experienced a heavy mass-loss episode just prior to explosion (as we discuss below), the interaction of the SN with the circumstellar material (CSM) could produce a reverse shock which may promote fallback of the inner ejecta.

The second implication of our analysis is that the progenitors of some stripped-envelope SNe may have surprisingly large initial radii, perhaps R ~ 20 R☉ for SN 2010X and R > 100 R☉ for SN 2002bj. This is considerably larger than the expected radii of most WR stars, R⊙ ~ few R☉. Recent stellar evolution models suggest that some stars with helium envelopes can have radii of the order of 10 R☉ (Yoon, Woosley & Langer 2010). However, for SN 2010X we favour a composition dominated by oxygen, not helium. In the absence of some refinement of our understanding of stellar evolution, the large inferred radius presumably requires some mechanism to puff up an oxygen star prior to explosion.

One compelling explanation for the large radius is mass-loss shortly before explosion. There are both observational and theoretical indications that instabilities can drive significant outflows from massive stars during the late stages of evolution (Woosley, Blinnikov & Heger 2007; Smith et al. 2011; Quataert & Shiode 2012; Smith & Arnett 2013). Most studies have focused on mass-loss episodes occurring ~years prior to core collapse, which could explain the most-luminous SNe observed (Smith et al. 2007; Gal-Yam 2012; Quimby 2012). If the expelled mass expands at roughly the escape velocity of a compact star (~1000 km s^-1), it will form a circumstellar shell at rather large radii, R ~ 10^15 cm. This shell, if it is optically thick, sets the effective ‘radius’ of the progenitor, which can produce a very bright SN light curve (L ~ 10^32 erg, see equation 5).

The much fainter SN 2010X could be explained in a similar way if a circumstellar shell was located at a smaller radius, R ~ 20 R☉. This would imply a much shorter time delay (~1 d) between mass-loss and explosion. In fact, this dichotomy of time-scales could be tied to the basic nuclear physics of massive stars; the time-scale of the oxygen burning phase is ~1 yr, while that of the silicon burning phase is ~1 d. If mass is lost during silicon burning at ~1000 km s^-1, the resulting circumstellar material would have reached a radius of 10^2–10^3 cm at the onset of core collapse a day or so later, setting the stage for an SN 2010X-like event. Because the shell is
relatively close to the explosion site, any observational indications of interaction (e.g. narrow emission lines) would only be visible for a short time (∼1 h) after explosion.

Quataert & Shiode (2012) and Shiode & Quataert (2013, see also Smith & Arnett 2013) have presented an explicit mechanism for mass-loss related to core fusion. They show that waves excited by vigorous convection during oxygen burning can (under certain circumstances) propagate through the star and deposit energy of the order of $10^{47}$–$10^{48}$ erg near the surface, sufficient to unbind ∼$10 M_\odot$ in a red supergiant. They also show that for stripped-envelope stars, the sound-crossing time is short enough (∼$1$ d) for this mechanism to operate during silicon burning as well.

To explain the light curve of SN 2010X, the mass in the circumstellar shell (or inflated envelope) must be substantial enough to provide a sufficiently long light curve, which may require $M_{\text{csm}} \gtrsim 0.5 M_\odot$ (using equation 4 with a time-scale of ∼$20$ d, $E \sim 1$ B and $R \sim 20 R_\odot$). The energy needed to drive this amount of material from a compact star is $\gtrsim 5 \times 10^{50}$ erg. While this is only ∼$1$ per cent of the total energy released during silicon burning, most of the fusion energy is lost to neutrinos. In the specific models of Shiode & Quataert (2013), wave-driven mass-loss in stripped-envelope stars only ejects $\lesssim 0.01 M_\odot$ of material in the silicon burning phase. However, more efficient mechanisms for mass-loss may be possible (Smith & Arnett 2013), perhaps due to explosive burning episodes occurring when parcels of fuel are mixed downward into the hot core. Pulsational pair instabilities can in some circumstances also eject successive shells of material on the appropriate day time-scale, in particular for the lower range of helium core masses (Woosley et al. 2007). Pulsational pair instabilities may not only act as a precursor for SN 2010X-like events by expanding the radius, but could also produce oxygen-rich and nickel-free transients themselves if they were to occur in stars stripped of their hydrogen and most of their helium (Heger, private communication). In this case, the star would remain after the event and could subsequently undergo more mass ejections or explode as an SN.

There may be other ways to expand the effective radius of a stripped-envelope progenitor, perhaps related to stellar mergers or a common envelope phase in a binary system (e.g. Chevalier 2012). Alternatively, a large effective radius could be due to reheating of the SN remnant after it has expanded for a brief time. Dexter & Kasen (2013), for example, explore the possibility that the input of accretion power of a central black hole, fed by fallback material, can produce a diversity of SN light curves.

Though they have previously been seen as weak explosions, our analysis suggests that faint, fast SNe like SN 2010X may have more in common with the most-luminous SNe in the Universe, namely the superluminous SNe powered by interaction with circumstellar material. In both cases, the progenitors may be massive stars that have experienced heavy mass-loss just prior to explosion. The main distinction in the observed light curve may simply be in the timing of the main pre-SN mass-loss episode. Further detailed modelling is needed to investigate the dynamics of the interaction and the variety of outcomes, and to determine whether realistic progenitors can produce core-collapse SNe of this type.

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