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Observed fractions of core-collapse supernova types and initial masses of their single and binary progenitor stars

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ABSTRACT

We analyse the observed fractions of core-collapse supernova (SN) types from the Lick Observatory Supernova Search (LOSS), and we discuss the corresponding implications for massive star evolution. For a standard initial mass function, observed fractions of SN types cannot be reconciled with the expectations of single-star evolution. The mass range of Wolf–Rayet (WR) stars that shed their hydrogen envelopes via their own mass-loss accounts for less than half of the observed fraction of Type Ibc supernovae (SNe Ibc). The true progenitors of SNe Ibc must extend to a much lower range of initial masses than classical WR stars, and we argue that most SN Ibc and SN IIb progenitors must arise from binary Roche lobe overflow. In this scenario, SNe Ic would still trace higher initial mass and metallicity, because line-driven winds in the WR stage remove the helium layer and propel the transition from SN Ib to Ic. Less massive progenitors of SNe Ib and IIb may not be classical WR stars; they may be underluminous with weak winds, possibly hidden by overluminous mass-gainer companions that could appear as B[e] supergiants or related objects having aspherical circumstellar material. The remaining SN types (II-P, II-L and IIn) need to be redistributed across the full range of initial masses, so that even some very massive single stars retain H envelopes until explosion. We consider the possibility of direct collapse to black holes without visible SNe, but find this hypothesis difficult to accommodate in most scenarios. Major areas of remaining uncertainty are (1) the detailed influence of binary separation, rotation and metallicity; (2) mass differences in progenitors of SNe IIn compared to SNe II-L and II-P; and (3) the fraction of SNe Ic arising from single stars with the help of eruptive mass-loss, how this depends on metallicity and how it relates to diversity within the SN Ic subclass. Continued studies of progenitor stars and their environments in nearby galaxies, accounting for SN types, may eventually test these ideas.

Key words: binaries: general – stars: evolution – stars: mass-loss – supernovae: general.

1 INTRODUCTION

The observed fractions of various types of core-collapse supernovae (CCSNe) provide key information about the evolution and ultimate fates of massive stars. Because of their tremendous luminosity, SNe can potentially be used as diagnostics of mass-loss and the evolution of individual stars at great distances and in a variety of galactic environments, but only if we first understand how to map initial masses and evolution of different progenitor stars to the various types of SNe that they produce. If drawn from a stellar population that obeys a standard initial mass function (IMF), the observed fractions of different CCSN types constrain the ranges of initial mass for their progenitors, as well as the evolutionary paths they take before death. The aim of this paper is to explore how the IMF can be sampled in order to be consistent with the observed fractions of CCSN types.

The main observed types of SNe that we consider are II-P (plateau), II-L (linear), IIn (relatively narrow lines), IIb (transitional), Ib, Ic and Ibc-pec (see Section 2). Spectroscopic classification criteria for these are reviewed by Filippenko (1997). Pre-SN mass-loss of the progenitor star determines which of these types of SN is seen, stripping away various amounts of the star's H and possibly He envelopes before core collapse ejects the remaining envelope. SNe Ibc are the result of complete removal of the H envelope; SNe IIb have retained only a small H mass (typically <0.5 $M_\odot$) while SNe II-L and II-P have retained increasingly more of their H envelopes. SNe IIn are different in the sense that their spectral appearance is determined largely by shock interaction with circumstellar material (CSM) lost in the decades or centuries preceding core collapse.

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The three potential mechanisms for an SN progenitor's mass-loss are via steady winds, eruptive mass-loss or mass transfer due to Roche lobe overflow (RLOF) in a close binary system. Depending on which dominates, the amount of mass lost might not depend in a simple way on metallicity or on the initial mass of the progenitor star, making reliable predictions difficult without a more complete understanding of mass-loss. The evolutionary state – red supergiant (RSG), blue supergiant (BSG), luminous blue variable (LBV) and Wolf–Rayet (WR) stars of the WN and WC sequences – and hence the stellar radius at the time of explosion, are also important, although these can be considered as largely the *result* of mass-loss. Massive stars have substantial steady stellar winds through most of their lives (see Lamers & Cassinelli 1999), with either metallicity-dependent, line-driven winds in hot stars (Kudritzki & Puls 2000), or slow, pulsation/dust-driven winds in cool stars (Reimers 1977). Single-star evolution models adopt simple prescriptions for these steady winds (Meynet et al. 1994), and aim to predict the fates of massive stars as functions of initial mass and metallicity (e.g. Heger et al. 2003; Eldridge & Tout 2004).

Recent observational work, however, has demonstrated that the standard observational mass-loss rates used as input to these models are far too high; the standard mass-loss rates of hot stars (e.g. Nieuwenhuijzen & de Jager 1990; de Jager, Nieuwenhuijzen & van der Hught 1998) are reduced by factors of 3–10 when the effects of clumping are considered properly (Bouret, Lanz & Hillier 2005; Fullerton, Massa & Prinja 2006; Puls et al. 2006). There is also a parallel problem in cool star mass-loss rates – reduction of an order of magnitude to the standard Reimers formula for red giants may be required (Mészáros, Avrett & Dupree 2009), and it would be interesting if this also affects more massive RSG stars. These lower mass-loss rates have a profound impact on stellar evolution and SN progenitors, requiring us to turn to either eruptive mass-loss (Smith & Owocki 2006) or close binaries (e.g. Paczyński 1967) to make up the deficit. We will see that this turns out to be a major theme in explaining the frequencies of SN types.

The stripping of a star's H envelope due to mass transfer in RLOF binary systems has long been considered a likely mechanism to produce WR stars and the progenitors of SNe Ibc (e.g. Paczyński 1967; Podsiadlowski, Joss & Hsu 1992). Recent stellar evolution models attempt to account for this (e.g. Eldridge, Izzard & Tout 2008), but considerable uncertainty surrounds empirical estimates of binary fractions; see Kobulnicky & Fryer (2007) and references therein.

In addition to close binary evolution, a major uncertainty concerns the net effect of episodic and eruptive mass-loss during late stages of stellar evolution (Smith & Owocki 2006). These outbursts are observed to occur, and studies suggest that they shed more mass from a star than do steady winds (Smith & Owocki 2006). The importance of sudden, short-duration eruptive mass-loss is a concern for the predictive power of any stellar evolution model, none of which currently includes it. Observational clues from CSM interaction in SNe IIn indicate that heavy mass-loss sometimes occurs shortly before core collapse (e.g. Chugai et al. 2004; Smith & McCray 2007; Smith et al. 2007, 2008b, 2010); if heavy mass-loss is concentrated in brief events during the last few thousand years before core collapse, then the statistical distribution of end fates (i.e. SN types) will not necessarily reflect the observed relative fractions of WN, WC, RSG, LBVs and so on, which are determined by the time spent in each state. This is critical and potentially misleading, since many stellar evolution codes are linked to these observed fractions.

Another key point is that both binaries and eruptions are probably less sensitive to metallicity than line-driven winds of hot stars. Some studies have shown that the observed fraction of SNe Ibc compared to SNe II increases with metallicity, implying that metallicity-dependent winds play an important role (Prantzos & Boissier 2003; Prieto, Stanek & Beacom 2008; Boissier & Prantzos 2009). On the other hand, observations have also revealed a large population of WR stars in low-metallicity galaxies, which cannot be explained by stellar winds alone (Izotov et al. 1997; Brown et al. 2002; Crowther & Hadfield 2006). The broad-lined SNe Ic that accompany gamma-ray bursts (see Woosley & Bloom 2006 for a review) also seem to prefer low metallicity (Stanek et al. 2006; Modjaz et al. 2008).

There have been a few previous investigations of relative SN rates that our study builds upon. Cappellaro et al. (1997) examined the statistics from 110 SNe (including SNe Ia), deriving widely adopted rates of various SN types in different environments. More recently, Smartt et al. (2009) considered a volume-limited sample of nearby CCSNe and examined the relative fractions of SNe II-P, II-L, IIb, IIn, Ib and Ic, as we do. Our results are different from theirs, as described below, leading to some quite different implications for massive stars. Finally, Arcavi et al. (2010) have recently submitted a paper independent of our study using SNe from the Palomar Transient Factory (PTF), finding a difference in the relative fractions of SNe II, IIb, Ib, Ic and broad-lined Ic between large galaxies and dwarf galaxies. Since our survey did not adequately sample dwarf galaxies, the study by Arcavi et al. (2010) is complementary to ours, although we find significantly different relative fractions of SN types in large galaxies. We also consider direct detections of SN progenitor stars from pre-explosion data, discussed in considerable detail below and reviewed recently by Smartt (2009). Throughout, we include this information along with current ideas about massive single and binary stars.

Here we present and discuss the implications of the observed relative fractions of different types of CCSNe in a new volume-limited sample, measured during the course of the Lick Observatory Supernova Search (LOSS) conducted with the Katzman Automatic Imaging Telescope (KAIT; Filippenko et al. 2001). This follows a series of papers discussing LOSS. Paper I (Leaman et al. 2011) describes the method of deriving rates from LOSS data, Paper II (Li et al. 2011a) discusses the luminosity functions of SNe and gives a detailed discussion of how the different fractions of SN types were derived, and Paper III (Li et al., 2011b) presents relations with host galaxies and other details.

2 OBSERVED CCSN FRACTIONS

Fig. 1 shows a pie chart illustrating the relative fractions of different types of CCSNe derived from LOSS. These values are taken from the volume-limited fractions of all SN types derived in Paper II, with the thermonuclear (Type Ia) explosions subtracted from the sample. The relative fractions of the total for CCSNe are listed in Table 1, and these values are adopted throughout this work. See Paper II for further details on how these numbers are derived from our survey. Errors in Table 1 were estimated using a random Poisson number generator to sample from a list of fake SNe with fractions corrected for various observing biases, with 10^6 realizations. Paper II discusses this in more detail.

There are several important points to note here. This volume-limited sample of CCSNe excludes most of the so-called 'SN impostors' (e.g. Van Dyk 2010; Smith et al. 2011), which appear as relatively faint SNe IIn that are often discovered by KAIT. If we had

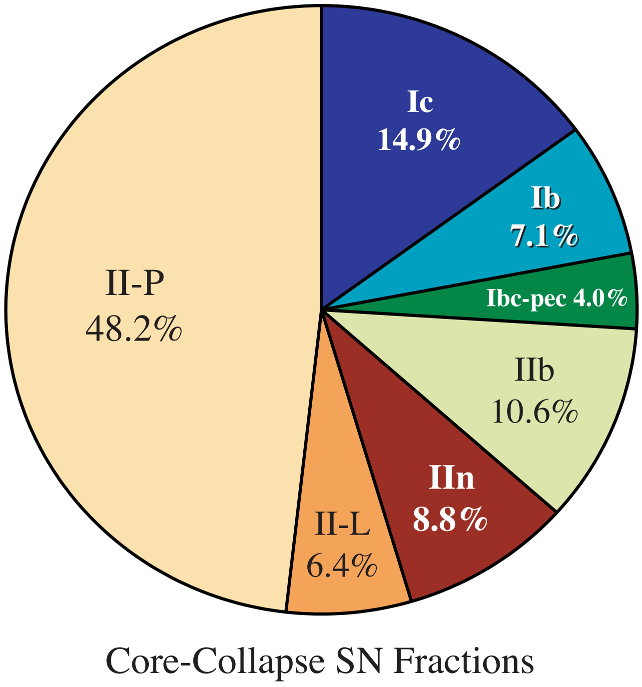

Figure 1. Relative fractions of CCSN types in a volume-limited sample from LOSS. This is slightly different from the fractions quoted in Paper II, in order to better suit the aim of this paper as explained in the text. The main difference is that we exclude SNe in highly inclined galaxies because of extinction effects, and we reorganize the class of SNe Ibc-pec (namely, we moved broad-lined SNe Ic from the 'Ibc-pec' category to the 'Ic' group).

included them, the fraction of SNe IIn would be significantly higher; note that even without the SN impostors, however, our relative fraction of SNe IIn is higher than in previous studies (Cappellaro et al. 1997; Smartt 2009). The criteria for excluding an individual SN impostor are admittedly somewhat subjective, but this is a necessary step since the diversity and potential overlap of SNe IIn and massive star eruptions are not fully understood yet. Generally, if an object has a peak absolute *R* or unfiltered magnitude brighter than −15 and has linewidths indicating expansion speeds faster than about 1000 km $\mathrm{s^{-1}}$, we include it as a real SN IIn. Less luminous and slower objects are considered impostors and are excluded.

Unlike previous studies, we include a category called 'SNe Ibc-pec' (peculiar; see Paper II). This category was necessary to introduce in Paper II because some SN Ibc vary significantly from the template light curves used to derive the control times for SNe Ib and Ic. As such, the 'Ibc-pec' category in Paper II includes some broad-lined SNe Ic such as SN 2002ap that are clearly SNe Ic. We have moved these to the SN Ic category for the purpose of this paper, since they clearly correspond to massive stars that have fully shed their H and He envelopes. This has a small effect on the overall statistics, because broad-lined SNe Ic are very rare in our sample, contributing only 1–2 per cent of all CCSNe. This is in agreement with the recent study of Arcavi et al. (2010), who find that broad-lined SNe Ic contribute only 1.8 per cent of CCSNe in large galaxies. It is noteworthy, however, that Arcavi et al. (2010) find broad-lined SNe Ic to be much more common (∼13 per cent of CCSNe) in low-metallicity dwarf host galaxies. We also exclude SNe occurring in highly inclined galaxies, where dust obscuration may introduce statistical problems that are difficult to correct. As a result of these minor adjustments, made because our goal of investigating implications for massive-star evolution is different from the goal of deriving relative rates and correcting for observational biases, the relative fractions of various SN types in Table 1 and Fig. 1 differ slightly from the results in Paper II.

Table 1. Volume-limited core-collapse SN fractions.

SN type	Fraction (per cent)	Error (per cent)
Ic	14.9	+4.2/−3.8
Ib	7.1	+3.1/−2.6
Ibc-pec	4.0	+2.0/−2.4
IIb	10.6	+3.6/−3.1
IIn	8.8	+3.3/−2.9
II-L	6.4	+2.9/−2.5
II-P	48.2	+5.7/−5.6
Ibc (all)	26.0	+5.1/−4.8
Ibc+IIb	36.5	+5.5/−5.4

In quoting fractions of various SN types, we ignore metallicity, galaxy class, and other properties, although we are cognizant of the importance of these properties and consider them in our discussion below. The galaxies included in the LOSS survey span a range of luminosity, with most of the CCSN hosts corresponding roughly to metallicities of 0.5–2 $\mathrm{Z_{\odot}}$ (Garnett 2002; the LOSS galaxy sample spans a range of M_K from about −20 to −26 mag, but most of the CCSN hosts are in the range of −22 to −25 mag; see Paper II). We note some trends in Paper II, such as the fact that SNe IIn appear to prefer lower luminosity spirals, whereas SNe Ibc seem to prefer large galaxies and therefore higher metallicity, consistent with previous studies (Prantzos & Boissier 2003; Prieto et al. 2008; Boissier & Prantzos 2009). LOSS is biased against very faint dwarf galaxies, since larger galaxies with potentially more SNe were targeted to yield a richer harvest of SNe. However, low-luminosity galaxies seem to have more than their expected share of star formation per unit mass, and probably contribute 5–20 per cent of the local star formation (Young et al. 2008). If unusually luminous SNe IIn and II-L favour such low-luminosity galaxies, as some recent studies may imply (Smith et al. 2008b; Miller et al. 2009; Quimby et al. 2009), then this may slightly raise the relative fractions of SNe IIn and II-L compared to our study. Recently commissioned untargeted surveys can help constrain this contribution (see Arcavi et al. 2010, as noted above regarding broad-lined SNe Ic in dwarf hosts).

Our volume-limited survey within 60 Mpc includes 80 CCSNe, compared to the heterogeneous volume-limited study of 92 CCSNe within 28 Mpc summarized by Smartt (2009). However, because the LOSS survey was conducted with the same telescope in a systematic way, we are able to make proper corrections for the observing biases, as Paper II describes in detail. We also have much more complete spectroscopic follow-up observations and we monitor the photometric evolution of the SNe we discovered, which particularly affects the relative fractions of SN II-P versus II-L, IIn and IIb, all of which are sometimes called simply 'Type II' in initial reports. Thus, samples of SNe using identifications from initial reports are often unreliable or unspecific, but our study resolves this issue because our more extensive photometric and spectroscopic follow-up observations allow us to more reliably place the SNe in subclasses. Consequently, our observed fractions of CCSN types differ from those of previous studies in a few key respects. The main differences compared to SN fractions listed in various studies reviewed by Smartt (2009) are as follows.

(1) We find a lower SN II-P fraction of only ∼48 per cent, in contrast to larger values of 59 per cent in previous studies, although some of these did not differentiate among SN II subtypes. This impacts the ‘RSG problem’ as discussed below.

(2) We find correspondingly larger fractions of SNe II-L, IIn and IIb compared with Smartt et al. (2009). This mostly reflects our spectroscopic and photometric follow-up observations mentioned above.

(3) We find a larger fraction of SNe Ibc than Cappellaro et al. (1997), although similar to other estimates (van den Bergh, McClure & Evans 1987; Prantzos & Boissier 2003; Prieto et al. 2008; Boissier & Prantzos 2009; Smartt et al. 2009). The number ratio of SNe Ibc to all SNe II that we measure is $N_{\rm Ibc}/N_{\rm II} = 0.35$, whereas Cappellaro et al. found a value for $N_{\rm Ibc}/N_{\rm II}$ of only 0.29. Prieto et al. (2008)[1] noted that $N_{\rm Ibc}/N_{\rm II} = 0.27$ in the full sample they considered, but they also found a metallicity dependence, with higher values comparable to ours at around solar metallicity. The high ratio we find is the crux of the ‘WR problem’ that we discuss herein.

3 THE IMF AND PROGENITOR MASSES

The IMF describes the relative number of stars as a function of initial mass, $N(m)$, and within a given mass range this dictates the distribution of initial masses for progenitors of SNe. We adopt a simple approximation of the IMF as a single power law and exponent γ given by

$$N(m) = Cm^{\gamma}, \tag{1}$$

where C is a constant. To understand the implications of SN rates for massive stars, we investigate the IMF within a mass range bounded by the lowest initial mass that results in a CCSN, $M_{\rm SN}$, and extending up to the upper mass limit for the initial masses of stars. One expects $M_{\rm SN}$ to be around 8 M$_{\odot}$, but there are uncertainties involved, as discussed further below. We take the upper limit to initial masses to be 150 M$_{\odot}$ (Figer 2005), although this choice has little effect on our analysis because the most massive stars are so rare in the local Universe (all the stars from 100 to 150 M$_{\odot}$ make up less than 2 per cent of the population, comparable to our uncertainties). A handy quantity is F_m, which we define as the fraction of all CCSNe contributed by stars with initial mass m or higher, up to 150 M$_{\odot}$. For an unbroken power-law IMF, this is given by

$$F_m = \int_m^{150} N(m')\mathrm{d}m' \tag{2}$$

$$= \frac{[1-(m/150)^{\gamma+1}]}{[1-(M_{\rm SN}/150)^{\gamma+1}]}, \tag{3}$$

where $\gamma = -2.35$ for a standard Salpeter (1955) mass function (note that this differs from the logarithmic form that is sometimes used, where Salpeter corresponds to $\Gamma = -1.35$). Bastian, Covey & Meyer (2010) have provided a recent review of the literature on possible variations in the IMF, and conclude that there is no clear evidence that the IMF varies strongly in the modern Universe. Clearly, $1 - F_m$ is the cumulative fraction contributed by stars between the lower bound ($M_{\rm SN}$) and m. This assumes that SN progenitors occupy the full mass range from $M_{\rm SN}$ to 150 M$_{\odot}$, with no large mass interval where stars consistently collapse directly to a black hole without any visual display (Fryer 1999); the latter remains a possibility, and implications are discussed later.

Figs 2 and 3 show plots of $1 - F_m$ and F_m, respectively, for three different representative values of $M_{\rm SN} = 8.0$, 8.5 and 9.0 M$_{\odot}$, as well as for two different values of $\gamma = -2.35$ (Salpeter 1955) or -2.4 (e.g. Humphreys & McElroy 1984) for comparison. One can see that small variations in γ have little effect on the results. Fig. 2 also illustrates a hypothetical case of $\gamma = -1.8$, which is large enough to make a substantial difference (this is the slope that would be needed to reconcile the disagreement between the observed fraction of SNe II-P and the observed mass range for the corresponding progenitors; see below). This slope, however, is more top-heavy than allowed by measurements of local stellar populations outside of the inner parts of the densest star clusters (see Bastian et al. 2010).

Small differences in the adopted value of $M_{\rm SN}$ can have a substantial effect, however. This is due to the fact that lower-mass stars are so much more numerous in a bottom-heavy IMF, and small changes in $M_{\rm SN}$ therefore have a disproportionate influence on the distribution of SN types. This is relevant in regard to the still-uncertain lower bound to initial masses that experience Fe core collapse and those that may suffer less energetic explosions via electron-capture SNe (ECSNe). According to Smartt (2009), directly observed RSG progenitors of normal SNe II-P extend down to around 8 M$_{\odot}$ and their statistical distribution favours $M_{\rm SN} = 8.0 \pm 1.0$ M$_{\odot}$. On the other hand, theories for ECSNe predict that these explosions occur somewhere in the range of 8–11 M$_{\odot}$ depending on assumptions about metallicity, mass-loss and other factors (Nomoto 1984;

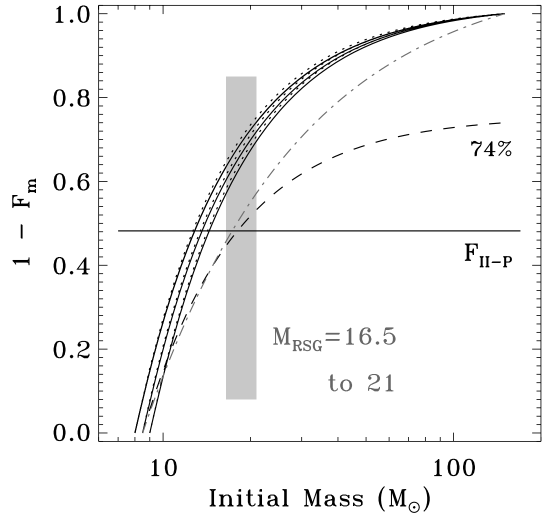

Figure 2. The quantity $1 - F_m$. This is a cumulative distribution function beginning at the bottom of the mass range for CCSNe ($M_{\rm SN}$), showing the fraction of CCSNe contributed by stars in the mass range from $M_{\rm SN}$ up to m. The three solid black curves are for three example values of $M_{\rm SN} = 8.0$, 8.5 and 9.0 M$_{\odot}$ using a Salpeter slope of $\gamma = -2.35$. The dotted curves are for $\gamma = -2.4$, whereas the grey dot–dashed curve illustrates the hypothetical top-heavy case of $\gamma = -1.8$ (see text). The long-dashed curve labelled ‘74 per cent’ shows the same function for $M_{\rm SN} = 8.5$ M$_{\odot}$ and $\gamma = -2.35$, but it excludes 26 per cent of the total number (26 per cent is the sum of the fractions of all SNe Ibc), assuming that they follow a different evolutionary path in close binaries over the full mass range considered; this possibility is discussed later in Sections 4.2 and 4.3. The grey box denotes the range of uncertainty in the upper bound to RSG progenitors of SNe II-P, based on the properties of progenitors detected so far (Smartt et al. 2008). The horizontal line is the observed fraction of SNe II-P.

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[1] Note, however, that Prieto et al. used the Sternberg Astronomical Institute (SAI) SN catalogue, which is a heterogeneous sample with unknown systematic biases.

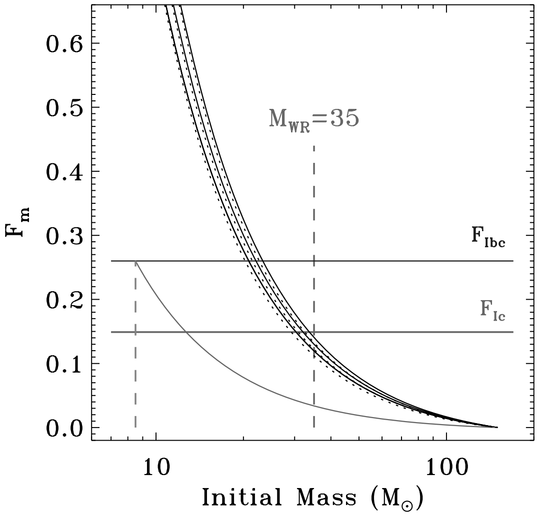

Figure 3. The quantity F_m (equation 3). This is similar to Fig. 2, but with a cumulative distribution function beginning at the *upper* mass limit and working down, showing the fraction of stars in the mass range between *m* and the assumed upper mass limit at 150 $M_\odot$. The horizontal lines mark the observed fractions of SNe Ic and the sum of SNe Ib + Ic + Ibc-pec. The vertical dashed line at $M_{WR} = 35$ $M_\odot$ marks the initial mass above which H-free WR stars are thought to originate, inferred from observations. The grey curve is the same as the solid black curve corresponding to $M_{SN} =$ 8.5 $M_\odot$, but multiplied by 0.26 to mimic the distribution of SNe Ibc if they were evenly distributed across the full mass range.

Woosley, Heger & Weaver 2002; Kitaura, Janka & Hillebrandt 2006; Pumo et al. 2009; Wanajo et al. 2009). Theory generally predicts that if ECSNe occur within this range, they would tend to be less energetic and fainter than a standard Fe CCSN, releasing $\sim 10^{50}$ erg of kinetic energy (instead of $\sim 10^{51}$ erg) and producing less ^{56}Ni than standard CCSNe. It has been hypothesized that an ECSN may have given birth to the Crab nebula (Davidson, Walborn & Gull 1982; Nomoto 1984; Kitaura et al. 2006; Wanajo et al. 2009).

A note of caution is that if the corresponding observed visual displays are indeed much fainter than normal CCSNe, then it is possible that some of these ECSNe may not be included in the LOSS sample, since we chose to exclude faint Type IIn events such as SN impostors, η Car analogs, LBVs or other peculiar faint transients in the observed fractions of CCSNe (Paper II). On the other hand, if ECSNe do not give rise to these SN impostors, but appear instead as the relatively faint end of the distribution of SNe II-P (objects like SN 2005cs; Pastorello et al. 2007), then they will be included in the LOSS rates as SNe II-P. The luminosity functions in Paper II reveal an enhancement at the very bottom of the luminosity range of SNe II-P. This uncertainty is unfortunate, but the ECSN phenomenon is not understood sufficiently well to confidently account for it. For this reason, Figs 2 and 3 show values for M_{SN} of 8.0, 8.5 and 9.0 $M_\odot$ and the range of uncertainty that this introduces.

Independent of the questions surrounding ECSN theory, however, an empirical value of $M_{SN} = 8.0 \pm 1.0$ $M_\odot$ is favoured by Smartt (2009) based on the distribution of masses for directly observed SN II-P progenitors (although one must remember that this value is model dependent as well, and subject to systematic effects; see Smartt 2009 for details). We adopt $M_{SN} = 8.5$ $M_\odot$ for most discussion in this work. If the ECSN phenomenon occurs above 8.5 $M_\odot$, we consider it likely that those ECSNe will be included among the population of faint SNe II-P anyway, while those below could be excluded if they masquerade as faint transients or SN impostors (e.g. Thompson et al. 2009).

3.1 The RSG problem

Red supergiants (RSGs) represent the expected endpoint of post-main-sequence stellar evolution for the majority of single stars with initial masses above 8 $M_\odot$, and it is straightforward to associate their extended H-rich envelopes with SNe II-P – the most common type of CCSN. This has long been expected (e.g. Falk & Arnett 1977; Litvinova & Nadyozhin 1983; Doggett & Branch 1985; Wheeler & Swartz 1993), but the RSG/II-P connection has received firm footing in the past decade with the identification of RSGs as the progenitor stars of several SNe II-P. This work has been based on attempting to locate progenitor stars (or upper limits to them) in pre-explosion archival data at the same position as the SN (Barth et al. 1996; Van Dyk et al. 1999; Smartt et al. 2001, 2002, 2003, 2004; Van Dyk, Li & Filippenko 2003a,b,c; Li et al. 2005, 2006, 2007; Maund & Smartt 2005), and in some cases the RSG disappears after the SN has faded.

These multiple progenitor studies have reassured us that RSGs are the progenitors of SNe II-P, but what range of initial masses do they imply? There are many potential systematic errors involved: masses derived from progenitor luminosities rely upon model-dependent evolutionary tracks, and circumstellar dust that may have surrounded the progenitor could have been vapourized by the SN, causing the extinction derived towards the SN progenitor – and therefore its luminosity and mass – to be underestimated. Smartt (2009) has reviewed the recent literature on the identification of SN II-P progenitors as RSGs in pre-explosion data and discussed these systematics. All considered, Smartt (2009) argues that the available collection of SN II-P progenitor detections and upper limits favours 8.5–16.5 $M_\odot$ for the range of initial masses, adopting a normal Salpeter IMF, and Smartt et al. (2009) give an upper limit to initial masses of SN II-P progenitors of 21 $M_\odot$ with 95 per cent confidence. The upper limit in the range of 16.5–21 $M_\odot$ is shown by the grey shaded area in Fig. 2.

In our volume-limited sample of SNe, we find that SNe II-P constitute about 48 per cent of CCSNe (Fig. 1). This is a lower fraction than reported in previous studies (Smartt 2009; Smartt et al. 2009; note that several other previous studies did not explicitly separate SNe II-P from II-L or other SNe II). Fig. 2 compares this LOSS observed fraction of SNe II-P, F_{II-P}, to the quantity $1 - F_m$ (see equation 3), which is the fraction of CCSNe one expects integrating from the bottom of the CCSN range at $M_{SN} = 8.0$, 8.5 or 9.0 $M_\odot$ up to mass *m*.

From Fig. 2 we see that the initial mass range of 8.5–16.5 $M_\odot$ over which RSG progenitors of SNe II-P have been identified would provide more than enough SNe to account for the observed fraction of SNe II-P, under the assumption that all stars within this mass range explode as SNe II-P. In fact, stars in the initial mass range 8.5–16.5 $M_\odot$ would constitute roughly 62 per cent of all the stars above 8.5 $M_\odot$ (for $\gamma = -2.35$) that undergo core collapse, producing *too many* SNe II-P. The mass range 8.5–13.7 $M_\odot$ would be sufficient to produce the observed fraction of SN II-P.

Thus, there is apparently no RSG problem from the 'supply-side' point of view, in the sense that the observed range of masses for SN II-P progenitors supplies a *large enough* fraction of CCSNe. Looking more closely, however, there is a 'demand-side' problem in the sense that stars in the initial mass range of 8–17 $M_\odot$ – which are in fact observed to explode as SNe II-P – produce *too many* SNe II-P compared to the observed fraction of this SN subtype. Smartt et al. (2009) did not emphasize this discrepancy in their study, presumably because they concluded that SNe II-P constitute a larger fraction (∼59 per cent) of CCSNe, which would be in reasonable agreement with the observed mass range within their uncertainties, compared to our value of ∼48 per cent, which is discrepant. A suggestive solution is given by the dashed line in Fig. 2, which brings the observed fraction of SNe II-P and the mass range of detected SN II-P progenitors into agreement. This curve is the same as the value of $1 - F_m$ shown by the black curves ($\gamma = -2.35$; $M_{\rm SN} = 8.5$ M$_\odot$), but multiplied by 74 per cent. The motivation for this is that it assumes that the 74 per cent of CCSNe that are Type II are distributed evenly across all initial masses, and that therefore the 26 per cent of all SNe that are SNe Ibc have some different origin which is also distributed across all initial masses. This might be the case, for example, if all SNe Ibc arise from RLOF in binary systems. We return to this question later.

Note that our comment about the lack of any ‘supply-side’ RSG problem is different from the RSG problem pointed out by Smartt et al. (2009), which has to do with the fact that RSG stars in the initial mass range $17 < m < 25$ M$_\odot$ are observed to exist, yet they appear to be missing from the population of nearby SN II-P progenitors detected in pre-explosion data. Smartt et al. (2009) hypothesized that these missing progenitor stars may collapse directly to black holes without producing successful SNe. Another possible solution to this discrepancy, however, is that RSGs in this upper mass range continue to evolve into other types of progenitor stars before core collapse, such as yellow supergiants (YSGs), blue supergiants (BSGs), low-luminosity LBVs, or Wolf–Rayet (WR) stars, producing SNe of Types II-L, IIb, IIn, Ib or Ic. Smartt et al. (2009) mentioned this hypothesis but disfavoured it, in part because the number of SNe IIb + II-L + IIn was not enough to make up for the missing population of RSGs, plus other reasons concerning the inferred masses for LBVs and progenitors of events like SN 1993J and SN 1980K. However, we find that these arguments rely on unreliable assumptions and that they provide no compelling argument against the idea that RSGs in the initial mass range 17–25 M$_\odot$ may continue to evolve before exploding.

Furthermore, in the volume-limited sample from LOSS, we find that SNe II-L, IIb and IIn make up a larger fraction of the total SN II group, and SNe II-P have a lower fraction, compared to the study of Smartt et al. (2009). With this LOSS sample, we find that there are plenty of remaining SNe II besides SNe II-P to account for SNe resulting (eventually) from RSGs known to occupy the higher mass ranges above 17 M$_\odot$. Another objection stems from the assumption by Smartt et al. (2009) that LBVs (the likely progenitors of SNe IIn) arise exclusively from stars with initial masses above 40 M$_\odot$, but there is also a population of lower-luminosity LBVs that are thought to be stars in a post-RSG phase with initial masses of 20–40 M$_\odot$ (see Smith, Vink & de Koter 2004). In addition to LBVs, Smith, Hinkle & Ryde (2009a) noted that the most extreme class of RSGs with high mass-loss rates and initial masses of 25–35 M$_\odot$ could give rise to the lower-luminosity SNe IIn. Thus, these considerations alleviate two key objections to the idea that 17–25 M$_\odot$ stars produce other types of SNe that are not Type II-P.

There is growing empirical evidence that this is indeed the case, supported by direct detections of progenitor stars of SNe II-L, IIb and IIn (and II-pec). SN 2009kr is the first luminous SN II-L to have a progenitor star identified in pre-explosion images (Elias-Rosa et al. 2010b; Fraser et al. 2010), and it appears to be a YSG. Elias-Rosa et al. (2010b) estimate a likely initial mass for the YSG progenitor star of 18–24 M$_\odot$, and infer that it may bridge a gap in progenitor mass between SNe II-P and the more massive LBV progenitors of SNe IIn (see below). SN 2009hd in M66 also had a Type II-L spectrum, for which Elias-Rosa et al. (2010c) have identified another likely YSG progenitor, suggesting an initial mass in the range of 20–25 M$_\odot$. SN 2008cn is yet another possible YSG progenitor of a luminous SN II-P (Elias-Rosa et al. 2010a), although the large distance to this SN makes the progenitor identification less secure.

Of course, the first SN to have a progenitor identified in pre-explosion data was SN 1987A, whose classification was Type II-pec, and which was inferred to have an ∼18 M$_\odot$ BSG progenitor that was in a post-RSG phase (see Arnett 1987; Arnett et al. 1989). The progenitor of the SN IIb 1993J was inferred to be a $M_0 \approx 15$ M$_\odot$ K-type RSG with a large radius but small H envelope mass (Aldering, Humphreys & Richmond 1994; Filippenko, Matheson & Barth 1994; Van Dyk et al. 2002; Maund et al. 2004). In both cases, binary evolution was invoked to explain the status of the progenitors at the time of core collapse (Nomoto et al. 1993; Podsiadlowski et al. 1993; Aldering et al. 1994; Woosley et al. 1994). Lastly, so far only one SN IIn (SN 2005gl) has a progenitor star identified in pre-explosion data, and it was a massive LBV (Gal-Yam & Leonard 2009).[2]

Collectively, these results argue that RSGs in the range of masses above the observed range for SN II-P progenitors may indeed continue to evolve after the RSG phase due to further mass-loss (in either single- or binary-star evolution), to produce other types of SNe. This relieves the RSG problem proposed by Smartt et al. (2009), and removes the empirical motivation for inferring that massive stars in some mass range collapse directly to a black hole (BH) without a visible SN display. In fact, we find that the latter inference would introduce other problems that are at odds with the observed fractions of CCSNe, as discussed further below.

3.2 The WR problem

Unlike the detected progenitors of SNe II-P, II-L, IIb, and IIn, the progenitor stars that have shed their H envelopes to make SNe Ibc have never yet been identified directly in pre-explosion data.[3] The known stars that most naturally fit the bill for progenitors of SNe Ib and Ic are the Wolf–Rayet (WR) stars of the WN and WC subclasses, respectively, because of their relatively H-free surface composition and their small stellar radii (e.g. Woosley & Bloom 2006). The distribution of WR stars in galaxies appears marginally consistent with that of SNe Ibc, although this depends on metallicity (Leloudas et al. 2010).[4]

It is straightforward to expect that the WC subclass would explode to produce SNe Ic, but it is not so clear if the WN subclass explodes as SNe Ib, or if instead the WN stars should continue to evolve by virtue of their own mass-loss to become WC stars before exploding as SNe Ic. Evidence that some WN evolve to WC is that the WN/WC ratio is ∼1 in the Milky Way and higher at lower metallicity, whereas from LOSS we find that $N_{\rm Ib}/N_{\rm Ic}$ is only $\lesssim 0.5$. This interplay may be

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[2] A second case identified recently may be SN 1961V (Smith et al. 2011).

[3] One putative exception is SN 2010O, for which Nelemans et al. (2010) detect a variable X-ray source at the SN position in pre-explosion data. Nelemans et al. (2010) claim that this may have been a WR/black hole binary system, where SN 2010O was the second SN in the system when a WN star produced the observed SN Ib. The WN star itself was not detected, however.

[4] We do not include the group of luminous H-rich late-type WN stars, or WNH stars (Smith & Conti 2008), which are probably still in core-H burning and are more like O-type stars with enhanced winds.

luminosity and metallicity dependent (as discussed further below), and comparisons of WR and SN Ibc positions in galaxies give mixed results (Leloudas et al. 2010). The fact that no normal SN Ib or Ic has an identified progenitor star[5] makes the identification of luminous WR stars as the only progenitors of both SNe Ib and Ic uncertain.

Standard single-star evolution models (e.g. Meynet et al. 1994; Heger et al. 2003) predict that strong line-driven stellar winds at high luminosity will cause stars more massive than some threshold mass to completely shed their H envelopes. This leaves He cores that are observed as WR stars (e.g. Conti 1976), and which should explode to make SNe Ibc. For convenience, we define $M_{\rm Ibc}$ as the initial mass dictated by the observed fraction of SNe Ibc, above which all progenitors have fully shed their H envelopes before core collapse. From Fig. 3, we find that SN statistics from LOSS show that $M_{\rm Ibc} \approx 22\,{\rm M}_{\odot}$.

Similarly, we define $M_{\rm WR}$ as the initial stellar mass above which a massive star is expected to shed its H envelope. If standard single-star evolution applies, then we should find $M_{\rm Ibc} = M_{\rm WR}$. However, standard single-star evolutionary models such as those by Heger et al. (2003) predict a much higher value of $M_{\rm WR} = 34\ {\rm M}_{\odot}$ at solar metallicity, and they suggest that $M_{\rm WR}$ rises to even higher initial masses at lower metallicity due to the strong metallicity dependence of line-driven winds that are assumed to dominate. A problem recognized in recent years is that these single-star evolutionary models have used empirical prescriptions for mass-loss rates that are now known to be *far too high* by factors of 3–10 compared to observed mass-loss rates, as noted in Section 1. Using more realistic wind mass-loss rates would change the predictions significantly, such that single-star evolution would not be able to account for the population of WR stars or SNe Ibc, even at solar metallicity.[6] Smith & Owocki (2006) have discussed this, pointing out that giant LBV-like eruptions may provide a way to make up the deficit, but the mass range over which this applies is uncertain; eruptive mass-loss is probably dominant in only the most massive stars. Observations of WR stars associated with star clusters suggest a value of $M_{\rm WR}$ around roughly 35–40 ${\rm M}_{\odot}$ for most WR stars in the Milky Way (Schild & Maeder 1984; Humphreys, Nichols & Massey 1985; Massey, Johnson & DeGioia-Eastwood 1985; Massey, DeGioia-Eastwood & Waterhouse 2001; Massey 2003; Crowther et al. 2006; Crowther 2007). We therefore adopt $M_{\rm WR} = 35\ {\rm M}_{\odot}$ for the majority of WR stars at roughly solar metallicity.[7]

Fig. 3 highlights a serious problem with assigning classical WR stars as the exclusive progenitors of SNe Ibc. Namely, the fraction of all stars experiencing CCSN above $M_{\rm WR} = 35\,{\rm M}_{\odot}$ only accounts for about half the number needed for the observed fraction of SNe Ibc. To account for all SNe Ibc in this simple prescription – where more luminous stars have higher mass-loss rates and therefore become WR stars and SNe Ibc by virtue of their own mass-loss – would require that SN Ibc progenitor stars extend from the upper mass limit down to around 22 ${\rm M}_{\odot}$. In other words, the WR problem can be stated simply as

$$M_{\rm WR} \gg M_{\rm Ibc}. \tag{4}$$

According to Fig. 3, roughly half the SN Ibc population must originate from stars that are less massive than initial masses corresponding to the observed or theoretically expected population of WR stars. There are several possible solutions to this problem. (1) The WR phase for many lower-mass stars is not observed because it is extremely short lived, perhaps because eruptions in late evolutionary phases remove the remaining H envelope even down to lower masses than we normally associate with LBVs. In this case, however, some SNe Ibc should show signs of interaction with H-rich CSM at late times, because that H must have been shed recently, while only a few do. SN 2001em is one example (Chugai & Chevalier 2006; Schinzel et al. 2009; Van Dyk et al. 2009), but perhaps there are more where the CSM interaction is missed at very late times. (2) Alternatively, the population of H-free stars that correspond to the progenitors of almost half of SNe Ibc may be underluminous because of significant mass-loss in binary RLOF. If underluminous, their radiation-driven winds – and hence, their emission-line spectra – may be weak and so they are not discovered or identified observationally as classical WR stars. These may be hidden by brighter companion stars in binary systems (i.e. the overluminous mass gainers), making them more difficult to observe (e.g. Kochanek 2009). Smartt (2009) mentioned this as a potential explanation for the lack of any detection of SN Ibc progenitors so far. The idea that RLOF dominates the population of SN Ibc progenitors was suggested long ago (e.g. Branch, Nomoto & Filippenko 1991; Filippenko 1991; Podsiadlowski et al. 1992) but has been hard to confirm. We find, as discussed further below, that *this is the likely origin of at least half and possibly most SNe Ibc*.

This is not to say that the expectations of single-star evolution are completely irrelevant. While binary RLOF may be largely independent of metallicity and initial mass, stellar winds may still play an important role. RLOF in binaries provides a likely way to strip the H envelopes at any metallicity, but it is less likely to strip the He envelope except for the shortest-period systems. The same goes for shedding the H envelope via giant LBV-like eruptions, which may also be insensitive to metallicity (Smith & Owocki 2006). However, the *subsequent* evolution of the stripped He core – from one with a small residual H mass to one with H-free and He-rich composition, and eventually toward removal of the He layer as well – can be accomplished by the line-driven wind of the WR star itself, *which does depend strongly on both metallicity and luminosity (and therefore initial mass)*. This is supported by the observation that the ratio of WN stars to WC stars varies from ∼1 in the Milky Way to 5 and 10 in the LMC and SMC, respectively (e.g. Crowther 2007). Even as binaries, some of the SNe Ibc – in particular the SNe Ic – may therefore appear to obey expected trends of single-star evolution, where the most luminous and higher metallicity stars are more able to shed their He envelopes via radiation-driven winds or eruptions, leading to WC stars and SNe Ic. This may explain why studies of the positions of WR stars and SNe in their host galaxies find that

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[5] A pre-explosion source was identified at the position of the famous object SN 2006jc, but this is a highly unusual case. The pre-explosion object was seen only as a transient source in a brief eruptive phase 2 yr before the SN, and the subsequent SN was a very unusual event, probably an underlying SN Ic whose shock overtook a dense He-rich circumstellar shell to produce an SN Ibn with bright, relatively narrow He I lines in the spectrum (see Foley et al. 2007; Pastorello et al. 2007; Smith, Foley & Filippenko 2008a). Nevertheless, the $\sim 10^3\ {\rm km\,s^{-1}}$ speed of the pre-shock CSM seems consistent with a compact WR-like progenitor.

[6] Models with rotation (e.g. Meynet, Mowlvi & Maeder 2008) have been proposed to yield lower values of $M_{\rm WR}$ as low as $\sim 25\ {\rm M}_{\odot}$ that are in better agreement with $M_{\rm Ibc}$, but this is because they have even higher mass-loss rates, violating observational constraints even more severely; this makes rotation an unlikely solution.

[7] There is also evidence that some lower-luminosity early-type WN stars may originate from lower initial masses down to $\sim 25\ {\rm M}_{\odot}$ (Crowther 2007), but stellar winds at solar metallicity (and probably even LBV eruptions as well) are insufficient to strip their H envelopes. In close binary evolution, however, complete removal of the H envelope can occur at much lower initial masses down to $\sim 15\ {\rm M}_{\odot}$ or less (e.g. Podsiadlowski et al. 1992; Eldridge et al. 2008). We will return to this later.

WC stars and SNe Ic seem to imply higher initial mass and higher-metallicity environments (Kelly, Kirshner & Pahre 2008; Anderson & James 2009; Leloudas et al. 2010; see also Papers I, II and III), even if binary evolution or LBV eruptions dominate the removal of the H envelope. We emphasize that it will be quite important in future studies to distinguish between SNe Ib and Ic while studying SN statistics as functions of metallicity and redshift. By the same token, it may be important to distinguish among subtypes of SNe II, as discussed next.

3.3 The LBV problem

At odds with the standard scenario for the formation of WR stars as the descendants of the most massive stars with $M_0 \gtrsim 35\,\mathrm{M}_\odot$ is the uncertain fate of LBVs and their connections to SNe. In this standard scenario (e.g. Conti 1976), winds of O-type stars on the main sequence shed much of the H envelope, leaving a very brief ($\sim 10^4$ yr) transitional LBV stage at the end of core-H burning that finishes the job of forming H-free WR stars. Recent work (Bouret et al. 2005; Fullerton et al. 2006; Puls et al. 2006) has demonstrated that O-star winds are clumped and that their mass-loss rates are too weak, so it appears likely that LBV giant eruptions must dominate this mass-loss if WR stars are to form via single-star evolution (Smith & Owocki 2006). If these eruptions are not strong enough, the star will fail to shed much of its H envelope before core collapse, producing an SN IIn (Smith & Owocki 2006).

In fact, recent studies have provided mounting evidence that some LBVs explode as SNe before the stars are able to fully shed their H envelopes. Luminous SNe IIn, which are thought to be powered by shock interaction with dense CSM, require large masses of material ejected in sudden eruptions that occur within decades before core collapse, in some cases as high as 10–20 $\mathrm{M}_\odot$ (Chugai et al. 2004; Smith et al. 2007, 2008b, 2010; Woosley, Blinnikov & Heger 2007; Smith 2008). The large CSM masses for luminous events like SN 2006tf and SN 2006gy require very massive progenitor stars to account for the mass budget, since the large ejecta mass corresponds only to the H-rich envelope ejected just before core collapse (i.e. the true initial mass of the star also includes the He core and any mass shed during the star's lifetime). One hypothesis for the pre-SN mass ejections of SNe IIn is that they suffered pulsational pair instability ejections before core collapse, in which case *very* massive progenitor stars with $M_0 \geq 95\,\mathrm{M}_\odot$ are needed (Heger et al. 2003).

There are other, anecdotal signs of a link between LBVs and SNe IIn as well, having to do with their wind speeds, absorption profiles and circumstellar nebulae (Kotak & Vink 2006; Smith 2007; Trundle et al. 2008). Much more directly, Gal-Yam & Leonard (2009) showed that the LBV-like progenitor of the SN IIn 2005gl subsequently disappeared, providing a strong case that LBVs do in some cases explode as SNe IIn, despite the fact that no contemporary stellar evolution models predict this. Gal-Yam & Leonard inferred a high initial mass of $\gtrsim 50\,\mathrm{M}_\odot$ for the progenitor of SN 2005gl. The 'LBV problem', then, is the fact that LBVs or some other very massive, unstable H-rich stars explode as SNe IIn, even though current models expect very massive stars to shed their H envelopes.

If SNe IIn truly arise from massive LBV progenitors, exactly what ranges of initial mass are required? How can we divide the IMF such that very massive progenitor stars can yield *both* SNe IIn and the SNe Ic that are supposed to come from the WC descendants of very massive stars? What scenarios are consistent with the observed fractions of various types of CCSNe? We investigate this problem next.

4 HYPOTHETICAL SCENARIOS FOR DIVIDING THE IMF

Given the problems and complications between progenitor scenarios expressed in the previous section, we now address the problem from a simpler empirical point of view. Here we ask how one can subdivide the IMF of massive stars in a way that is consistent with the fractions of various CCSN types observed in LOSS, while also meeting requirements imposed by our knowledge of the likely progenitor stars. For simplicity, in all cases we adopt a Salpeter IMF within the mass range bounded by the lowest initial mass for which SNe occur, assumed to be $M_{\mathrm{SN}} = 8.5\,\mathrm{M}_\odot$, up to the proposed upper mass limit for initial masses at 150 $\mathrm{M}_\odot$ (Figer 2005).

This is meant to be exploratory and demonstrative, rather than definitive. We consider extreme hypotheses such as one where all massive stars obey expectations of single-star evolution (e.g. Heger et al. 2003), and alternatively, where all stripped-envelope SNe arise from binary RLOF (e.g. Filippenko 1991; Podsiadlowski et al. 1992), and we evaluate merits and drawbacks of each. We also mention a compromise 'hybrid' scenario. Our analysis is intended to guide intuition in future studies, and to provide tests for single and binary star population synthesis models.

4.1 Dominated by standard single-star evolution

We first consider the familiar hypothesis that at a given metallicity, increasingly more massive and more luminous stars have monotonically increasing mass-loss rates, such that higher initial masses invariably lead to greater stripping of the H and He envelopes. It is essentially a hypothesis that single-star mass-loss dominates over close binary interactions in stripping a massive star's envelope, thereby determining the distribution of SN types. This is widely considered to be the 'standard' view of mass-loss connecting stellar initial masses to their ultimate fates as a function of metallicity (e.g. Heger et al. 2003). In this picture, the most massive stars fully shed their H envelopes by virtue of their own strong winds or LBV-like eruptions to produce SNe Ibc. At intermediate masses, stars do not fully shed their H envelopes, instead producing SNe IIn, IIb and II-L, depending on how much H mass was lost, and how recently this occurred (i.e. the density of the immediate CSM). The lowest mass range corresponds to RSGs that do not shed their H envelopes and produce SNe II-P.

Fig. 4 shows how the IMF would need to be subdivided in this hypothetical single-star framework, dictated by the observed fractions of various SNe types determined by LOSS (Fig. 1). Fig. 4 is largely a more succinct restatement, in graphical form, of the discussion above concerning inconsistencies with RSGs, WR stars and LBV progenitors.

While in principle this scenario is consistent with the qualitative expectation that more massive stars have stronger pre-SN mass-loss, it also comes with many inconsistencies, and conflicts with several observational constraints on the likely progenitors of various SN types. Some obvious problems evident from Fig. 4 are the following.

(1) The mass range occupied by the observed fraction of SNe II-P (8.5–13.7 $\mathrm{M}_\odot$) is too small compared to the directly observed mass range of SNe II-P progenitors, 8.5–17 $\mathrm{M}_\odot$ or more (Smartt 2009). In other words, if all stars in the range 8.5–17 $\mathrm{M}_\odot$ produced SNe II-P, then the fraction of CCSNe that are II-P would be much higher than observed.

(2) This scenario contradicts the observational indication that some SNe IIn have very massive LBV-like progenitors, as discussed

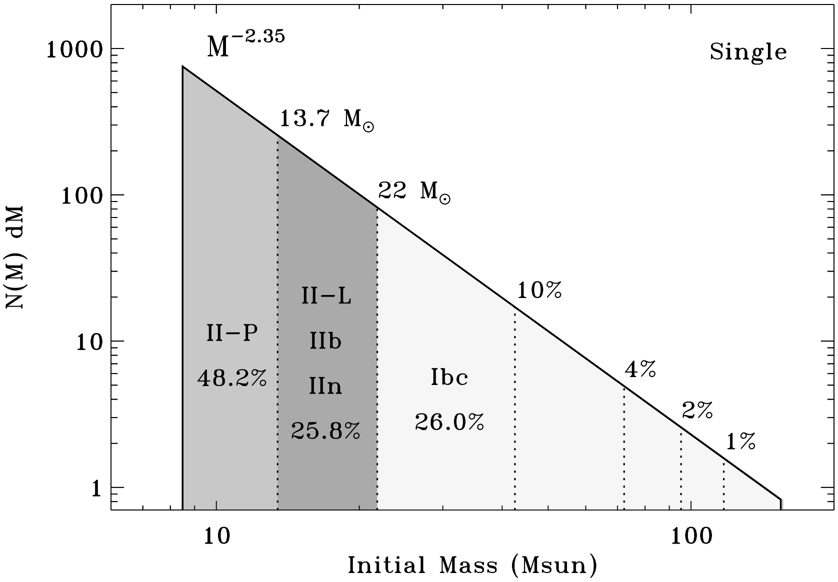

Figure 4. Mass ranges implied by the observed fractions of SN types in a standard single-star evolutionary framework, where higher initial masses lead to higher mass-loss rates, and consequently greater stripping of the H and He envelopes. $M_{\rm Ibc} \approx 22\,{\rm M}_{\odot}$ is the dividing point above which stars must fully shed their H envelopes in this scenario.

above. A few SNe IIn appear to have progenitors with initial masses of at least 50–80 $\mathrm{M}_{\odot}$, whereas Fig. 4 requires that no stars above 22 $\mathrm{M}_{\odot}$ retain any H envelopes at core collapse.

(3) Similarly, recent identifications of yellow supergiants as SNe II-L progenitors place them at the upper extreme of the range allowed for SNe II, or even above 22 $\mathrm{M}_{\odot}$. Masses inferred for the SNe II-L 2009kr and 2009hd are 18–24 $\mathrm{M}_{\odot}$ and 20–25 $\mathrm{M}_{\odot}$, respectively (Elias-Rosa et al. 2010b; 2010c).

(4) Most importantly, there are far too many observed SNe Ibc, requiring that all stars above 22 $\mathrm{M}_{\odot}$ completely shed their H envelopes, whereas the expected value $M_{\rm WR}$ is roughly 35 $\mathrm{M}_{\odot}$. Even at solar metallicity, stars below $M_{\rm WR}$ do not have sufficiently high mass-loss rates to shed their H envelopes – certainly not through metallicity line-driven winds or RSG winds, and probably not through LBV eruptions either. The known initial mass range for most nearby WR stars accounts for only half the SN Ibc population.

We regard this disagreement as strong evidence that standard single-star evolution with mass-loss simply cannot account for the observed distribution of SNe types, and that binary RLOF is therefore needed to account for at least half of the SN Ib/Ic population, possibly most of it (this is the next case discussed below).

Introducing the hypothesis that some stars collapse directly to BHs without making a visible SN does not help. If we assume that the most massive stars collapse to BHs (with >40 $\mathrm{M}_{\odot}$, for example; Fryer 1999), then it pushes the dividing mass between SNe II and SNe Ibc to even lower values, making the problem worse. It would also push the upper mass for SN II-P progenitors even lower, causing an even worse discrepancy with direct progenitor mass estimates. A partial solution relying on BHs would require a finely tuned or carefully chosen set of intermediate mass ranges for BHs, but it is still unsatisfactory (i.e. assuming that stars of, say, 20–30 $\mathrm{M}_{\odot}$ initial mass collapse to BHs could bring the mass range of SNe Ibc into better agreement with $M_{\rm WR}$, but it would worsen the problem in points 1–3 above). Direct SN-less collapse to a BH may nevertheless be a possibility. Better constraints on the disappearance of stars without SNe are needed (e.g. Kochanek et al. 2008).

4.2 Dominated by close binaries #1

An alternative to single-star mass-loss is that mass ejection or mass transfer via RLOF in interacting binaries plays a dominant role in stripping away the H envelope for a significant fraction of SN progenitors. This binary hypothesis for explaining WR stars and SNe Ibc has been around longer (Paczyński 1967) than the idea that stellar winds of single stars remove the H envelope (Conti 1976). Several studies of the effects of binary RLOF on massive star evolution have been conducted (e.g. Podsiadlowski et al. 1992; Wellstein & Langer 1999; Vanbeveren, Van Bever & Belkus 2007; Eldridge et al. 2008). It has been difficult to confirm or refute the idea that binary RLOF dominates the removal of the H envelopes in massive stars because of uncertainties in the binary fraction as a function of initial mass (see Kobulnicky & Fryer 2007) and the large number of free parameters in binary models. Also, until very recently (when mass-loss rates of hot stars have been revised downwards), single-star evolution seemed to provide a sufficiently plausible alternative. We argue here that low mass-loss rates of single stars combined with the large SN Ibc fraction now *demand* that binary RLOF plays a dominant role for a large fraction of SNe Ibc.

Fig. 5 shows a simplified scenario that is radically different from Fig. 4. It represents the other extreme where, instead of assuming that all stars shed their H envelopes via their own winds in single-star evolution, we adopt the opposite premise that *all* SNe Ibc have lost their H envelopes via RLOF in binary systems (following Filippenko 1991; Podsiadlowski et al. 1992; Fryer, Burrows & Bez 1998; Fryer, Woosley & Hartmann 1999; Kobulnicky & Fryer 2007; Eldridge et al. 2008). To create Fig. 5, we simply assumed that the observed fraction of SNe Ibc, ∼26 per cent, is identical to the fraction of massive stars that lose their H envelopes in RLOF, and that the remaining H-bearing SNe are distributed across the full mass range. We of course do not know the binary frequency as a function of

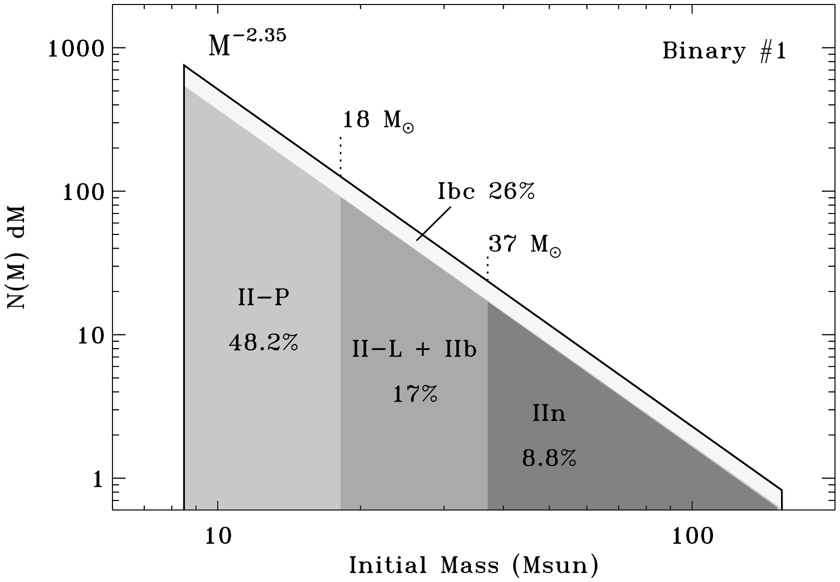

Figure 5. Same as Fig. 4, but now assuming that close binary evolution and RLOF is a necessary ingredient to explain the loss of the H envelope for all SNe Ibc. In this 'Binary #1' scenario, the fraction of all massive stars that lose their H envelopes in this way is determined to be 26 per cent, which is the same as the observed fraction of SNe Ibc. For simplicity, these binaries are divided equally among all initial masses; consequently, the remaining stars that fail to shed their H envelopes (all SNe II) are redistributed across the full range of initial masses as well, following expectations that more massive stars have higher mass-loss rates.

initial mass, so for simplicity, this 26 per cent is then distributed evenly across all initial masses of SN progenitors.

This simple 'Binary #1' scenario has some advantages over the standard single-star hypothesis, as well as some drawbacks, as follows.

(1) The initial mass range of 8.5–18 M$_\odot$ occupied by the ~48 per cent of CCSNe that are SNe II-P is now in much better agreement with the inferred mass range of RSG progenitors (Smartt 2009).

(2) The mass range of SNe II-L is in better agreement with recent detections of progenitors mentioned above, although perhaps somewhat too high, and it is unclear how the difference between SNe II-L and IIb arises naturally in this scenario.

(3) By redistributing the remaining SNe II over all initial masses, this scenario allows for SNe IIn to be associated with the most massive stars, consistent with their presumed massive LBV progenitors and with the pulsational pair instability in the most extreme cases. This scenario also has the appealing characteristic that the H-rich sequence II-P → II-L/IIb → IIn corresponds to a sequence of single progenitors with increasing mass-loss rate, and hence SNe with increasing CSM interaction.

(4) Owing to the fact that SNe Ib are relatively rare, the mass range of SNe Ib (including SNe Ibc-pec) is surprisingly narrow and low, at only 8.5–12.4 M$_\odot$, if they occupy lower masses than SNe Ic within the binary zone in Fig. 5. There are currently no direct detections of SN Ib progenitors.

A potential objection to this simple binary scenario is that the fraction of SNe Ibc compared to SNe II is observed to be metallicity dependent (Prantzos & Boissier 2003; Prieto et al. 2008; Boissier & Prantzos 2009; Papers I, II and III), as are different WR subtypes (Crowther 2007), and that SNe Ic are thought to be associated with massive stars and higher metallicity because of their specific locations in galaxies (Kelly et al. 2008; Anderson & James 2009; Papers I and II). However, this may still be true even in the simple binary scenario. Binary RLOF is only effective at removing the H envelope in most cases, leaving the He core exposed. More massive and luminous stars will have stronger winds with higher radiation-driven mass-loss rates, which will dominate the *subsequent* evolution. Consequently, only more massive stars (or perhaps the closest binaries) experience further significant mass stripping, driving evolution from WN to WC to produce SNe Ic rather than SNe Ib. A corollary is that line-driven winds of WR stars are metallicity dependent, so while removal of the H envelope (either by RLOF or LBV-type eruptions) is insensitive to metallicity, the further evolution from WN to WC (and hence, the production of SNe Ic) will be highly dependent on metallicity.

One last complication is that this scenario places SNe IIb as single stars and SNe Ib as binaries. This leaves us without a satisfactory explanation as to why such a tiny difference in surface H mass separates SNe IIb and SNe Ib (e.g. Filippenko et al. 1994; Elmhamdi et al. 2006; Chornock et al. 2010), which otherwise look extremely similar, and it ignores observational results suggesting that the progenitor of the nearby Type IIb SN 1993J was most likely a binary system (Aldering et al. 1994; Maund et al. 2004; Maund & Smartt 2009). There is also evidence for binarity in the case of SN 2001ig (Ryder et al. 2004; Ryder, Murrowood & Stathakis 2006; Maund et al. 2007; Silverman et al. 2009), which was also Type IIb. These issues motivate the alternative binary scenario discussed next.

4.3 Dominated by close binaries #2

The second binary-dominated progenitor scenario that we consider is similar to the first, except that we now include all SNe IIb along with SNe Ib and Ic as stars that lose their H envelopes primarily through binary RLOF. The motivation for this, as explained above, is the close morphological relationship between SNe IIb and Ib – SNe IIb essentially *are* Type Ib except for a small amount of H at early times – plus the observational evidence of the progenitor of SN 1993J and models for its evolution that are suggestive of a binary system (Podsiadlowski et al. 1993; Aldering et al. 1994; Maund et al. 2004; Maund & Smartt 2009).

Fig. 6 shows how the IMF could be divided according to observed SN fractions if we assume that all 'stripped-envelope SNe', now including SNe IIb along with SNe Ibc, arise from binary RLOF. Including SNe IIb as binary systems has three main consequences compared to the Binary #1 scenario.

(1) The fraction of all CCSNe progenitors that lose their H envelopes through binary RLOF is higher, at ∼37 per cent instead of ∼26 per cent. Note that both the cases Binary #1 and #2 imply rather high binary fractions, as the stripped-envelope progenitors are mainly the mass losers in RLOF binary systems, but the implied close binary fraction is within reason (see Kobulnicky & Fryer 2007).

(2) The upper mass bound for SN II-P progenitors is shifted to higher masses (23.6 $M_\odot$). This upper bound is somewhat troublesome, as it exceeds the 95 per cent confidence upper limit of 21 $M_\odot$ derived from the properties of SN II-P progenitors (Smartt et al. 2009).

(3) Most significantly, the mass range for SNe Ib shifts to higher-mass progenitors than in the Binary #1 scenario. Assuming that progenitors of SNe Ib are less massive than SNe Ic in the Binary #1 scenario would imply that SNe Ib arise from initial masses of 8.5–12.4 $M_\odot$; as noted above, this is low and quite narrow. If we assume the same for the Binary #2 hypothesis, but also add the assumption that SNe IIb, in turn, are less massive than SNe Ib, then the corresponding ranges of initial masses would be 8.5–11 $M_\odot$ for SNe IIb, 11–16 $M_\odot$ for SNe Ib and >16 $M_\odot$ for SNe Ic. This is an improvement over the Binary #1 scenario in that it pushes the dividing mass between SNe Ib and Ic to higher masses, although 16 $M_\odot$ still seems quite low for WR stars that we expect to shed their own He envelopes via line-driven winds. This is remedied in the 'hybrid' scenario discussed next. An important caveat is that the monotonic transition SNe IIb → Ib → Ic with increasing initial mass is probably not strict, as it also depends on initial binary separation (i.e. very close binaries can remove all of the H and even He layers in RLOF). Thus, SNe IIb could extend to higher masses than 11 $M_\odot$ if they arise in relatively wide binaries, for example (see below).

By dividing SN types into two different and distinct channels corresponding to single stars and binaries, the Binary #2 hypothesis has the appealing quality that it provides a natural continuity in SN types within each channel, which is lacking otherwise. With increasing levels of envelope stripping due to RLOF followed by WR wind mass-loss, the binary channel gives SNe IIb → Ib → Ic. There may be a continuum of SN progenitors with different levels of envelope stripping, probably corresponding to increasing initial metallicity or luminosity. Thus, a small amount of residual H separates SNe IIb and Ib (e.g. Elmhamdi et al. 2006; Chornock et al. 2010), whereas a small difference in He mass may separate SNe Ib from Ic.

In the Binary #2 hypothesis, there is also now a natural continuity in the single-star channel, giving SNe II-P → II-L → IIn with increasing initial mass and pre-SN mass-loss, and without the puzzling ambiguity between the origins of SNe IIb and II-L. The few direct detections of progenitors that are available support the notion that the progenitors of SNe II-L are more massive than those of SNe II-P (Elias-Rosa et al. 2010b,c), and that progenitors of SNe IIn are more massive than SNe II-L (Gal-Yam & Leonard 2009; Smith et al. 2011). The same is true for levels of CSM interaction: SNe II-P tend to have extremely weak or undetectable CSM interaction signatures, SNe II-L tend to have stronger radio and X-ray emission (Sramek & Weiler 1990), and their Hα profiles with weak P-Cygni features are thought to arise from heating of the SN ejecta by CSM interaction (e.g. Chugai 1991). SNe IIn obviously have the strongest levels of CSM interaction, but there is wide diversity even among the subclass, with the faintest SNe IIn like SN 2005ip looking basically like an SN II-L with strong narrow emission lines (Smith et al. 2009b), whereas the CSM is opaque and qualitatively changes the SN in more luminous SNe IIn such as SN 2006tf and SN 2006gy (Smith et al. 2008b). The full range for SNe IIn (34–150 $M_\odot$) encompasses the most luminous RSG that may be responsible for the fainter SNe IIn (Smith et al. 2009a; see also Yoon & Cantiello 2010), intermediate cases of SNe

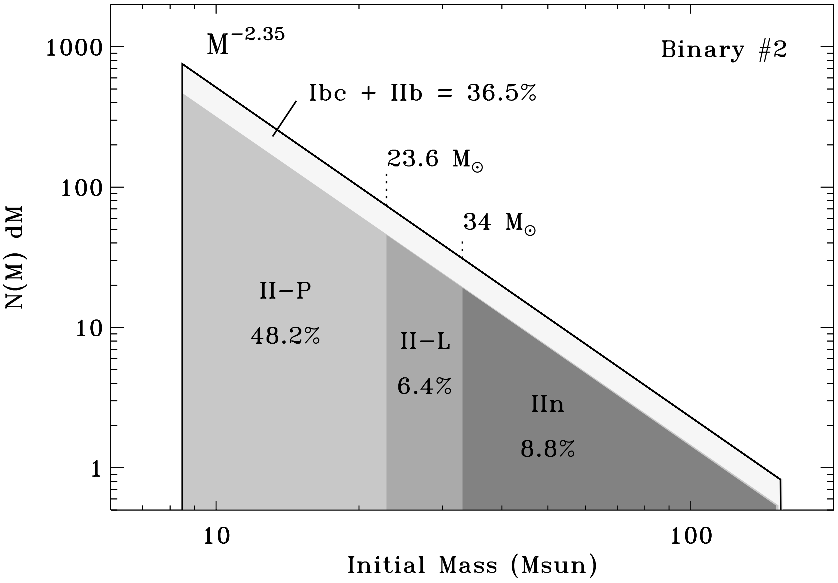

Figure 6. Same as Fig. 5, except that we have included SNe IIb in the same group with SNe Ibc, all of which are assumed to have their envelope stripping dominated by RLOF in close binary systems.

IIn consistent with normal LBVs (Gal-Yam & Leonard 2009), as well as the most massive stars with violent pre-SN mass-loss (Smith et al. 2007, 2010; Woosley et al. 2007).

If we relax the requirement that all of the most massive single stars make successful SNe IIn, then the lower-right corner of Fig. 6 provides an attractive parameter space for massive stars that can collapse to a BH without making an SN display. If, for example, we allow all *single* stars above 50 M$_{\odot}$ in the Binary #2 scenario to quietly make BHs, then the redistribution of the remaining mass ranges for SNe II-P, II-L and IIn are still in rough agreement with observational constraints. Of course, this would fail to produce the very luminous SNe IIn that are thought to come from the most massive stars.

A drawback of this Binary #2 scenario is that the initial mass range for SNe Ic still reaches uncomfortably low masses, and therefore dominates most of the mass range for binary progenitors. Note that if we allow some of the most massive stars in the binary channel to undergo a quiet BH collapse, we would need to shift the boundary between SNe Ic and Ib to even lower initial masses, exacerbating this problem. Also, the Binary #2 scenario does not allow any SNe Ic to come from single stars. This raises the question of the origin and fate of single WR stars, which presumably arise from eruptive LBV mass-loss in very massive stars or perhaps through strong winds at supersolar metallicity. The next scenario allows some of the most massive single stars to produce SNe Ic as well.

4.4 A hybrid scenario

One can, of course, play this game *ad nauseum* by adjusting the fraction of SN progenitors that experience binary RLOF, and redistributing the remainder among single stars in various ways. Fig. 7 shows an example of one 'hybrid' scenario, which is a compromise between the standard view of single-star evolution and the Binary #2 scenario. Here we have assumed that roughly half of the SN Ic population (we take a fraction equal to 8.8 per cent of all CCSNe for convenience, equal to the SNe IIn fraction) may arise from single-star evolution, while the remainder of SNe Ic form via binary RLOF along with SNe Ib (including Ibc-pec) and SNe IIb as before, so that the binary RLOF fraction is 28 per cent in this hypothetical scenario. The binary fraction may be somewhat different or may be mass dependent, and one can adjust a version of Fig. 7 accordingly to match precise values; the goal here is to be conceptual.

Although such a scenario may seem more complicated and somewhat ad hoc, it is well motivated, and balances several competing factors. Among the most massive stars with initial masses above 23 M$_{\odot}$, it allows single stars to die as *either* SNe Ic or IIn. This may be the case if the efficiency of single-star mass-loss depends on additional factors such as rotation or metallicity. One can imagine, for example, that very massive stars may be unable to shed their H envelopes if low metallicity or slower initial rotation rates weaken their winds or tame the LBV instability. Under these circumstances, massive stars might then die as SNe IIn if they suffer core collapse while still in the process of attempting to shed their H envelopes. Indeed, we noted in Paper II that SNe IIn tend to prefer smaller, lower-metallicity galaxies. The remainder of more rapidly rotating single stars or higher-metallicity single stars might successfully shed their H envelopes via winds or LBV eruptions and die as SNe Ic. LBV eruptions do seem to be more catastrophic among the most massive stars (Smith & Owocki 2006).

Aside from being hypothetical, this scenario has no obvious disadvantages in view of our knowledge of SN progenitors, and it has some strengths as follows.

(1) It maintains very good agreement between the mass range of SNe II-P and the inferred mass range of directly detected RSG progenitors (Smartt 2009). Putting some of the SNe Ic back into the single-star channel has the consequence that it lowers the upper mass bound required for SNe II-P compared to the Binary #2 scenario, improving the agreement with observations. Obviously, we could

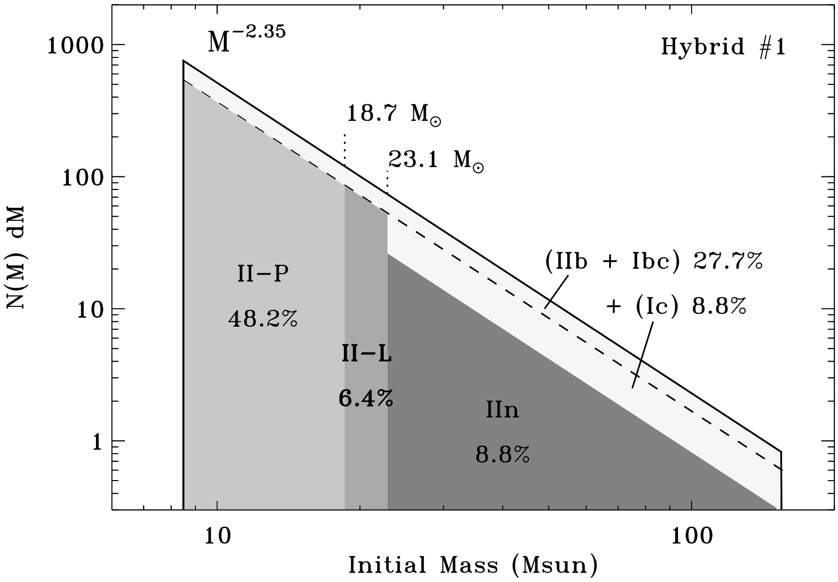

Figure 7. Our favoured scenario, combining single and binary star evolution. This is the same as Fig. 6, except that now we have taken roughly half of the SNe Ic (8.8 per cent of all CCSNe, to match the fraction of SNe IIn) away from the binary RLOF population and mixed them with the single-star population. SNe Ic that arise from single stars are below the dashed line. Thus, in this scenario we assume that half of all single stars above ~23 M$_{\odot}$ are able to shed their H envelopes via winds or LBV eruptions, while the other half retains their H envelopes until just before core collapse, producing SNe IIn. The difference among the most massive stars would depend on the efficiency of winds and LBV eruptions, which in turn may depends on properties such as metallicity or rotation. The specific numbers shown here are meant to provide just one example of a potential hybrid scenario.

have chosen the fraction of SNe Ic to be a little larger in order to precisely match the upper mass range for SNe II-P.

(2) The mass range of SNe II-L, albeit narrow, is entirely consistent with known progenitors of this class mentioned earlier.

(3) Fig. 7 allows SNe IIn to arise from among the most massive stars, consistent with their hypothesized LBV or pulsational pair instability progenitors. As in the Binary #1 and #2 scenarios, it provides for the apparent continuity in pre-SN mass-loss from SNe II-P to II-L to IIn. The initial mass range of SNe IIn progenitors is roughly 23–150 $M_{\odot}$, commensurate with the known initial mass range of LBVs (Smith et al. 2004). We show an alternative version of a hybrid scenario in Fig. 8, wherein we separate SNe IIn and single-star SNe Ic by mass, instead of dividing them half-and-half across all single-star masses above 23 $M_{\odot}$. This is very similar in principle to the original standard single-star hypothesis (Fig. 4), but with SNe IIb, Ib and some Ic now excluded as binaries. In Fig. 8, the dividing mass between SNe IIn and single-star SNe Ic is $\sim$36 $M_{\odot}$. This has the advantage that classical LBV eruptions above this mass can account for the mass-loss to produce SNe Ic, but it has the disadvantages that it does not allow SNe IIn to arise from the most massive stars, and it does not allow for other factors like luminous SNe IIn preferring low metallicity, or rapid rotation working across a range of masses. For these reasons, we tend to favour Fig. 7 over Fig. 8, but the truth may be somewhere in between. Differentiating between these two possibilities is difficult, since we do not yet know how to distinguish single-star from binary SNe Ic.

(4) As in the Binary #2 scenario, SNe IIb arise in binaries, consistent with the progenitor of SN 1993J (see above). The initial mass range of SN IIb progenitors in this scenario, if they occupy the low-mass end of RLOF binaries, would be 8.5–12 $M_{\odot}$. This is admittedly quite low, and perhaps lower than expected for the progenitors of SN 1993J ($\sim$15 $M_{\odot}$; Young et al. 2006) and the SN IIb that gave rise to Cas A (Krause et al. 2008; Rest et al. 2008), given the strong N enrichment in its CSM (Chevalier & Kirshner 1978; Fesen & Becker 1991; Chevalier & Oishi 2003). An alternative interpretation may be that initial rotation rates, metallicity or especially binary separation also play a role here, so that some of the SN IIb and SN Ib progenitors overlap in mass range up to 25 $M_{\odot}$ depending on these conditions. The wider mass range would allow more diversity in the progenitors of SNe IIb, consistent with the expectations of Chevalier & Soderberg (2010). Still, studies thus far have revealed no surviving companion star for Cas A (Thorstensen, Fesen & van den Bergh 2001; Krause et al. 2008), so there may be exceptions where some massive single stars produce SNe IIb as well. On the other hand, we note that Podsiadlowski et al. (1992) expect cases where the original secondary star that gains mass in RLOF may experience accelerated evolution and explode first, leaving a widowed SN IIb or SN Ib progenitor to explode as an apparently single stripped-envelope star. Perhaps something like this occurred in Cas A.

(5) The hybrid scenario gives an appealing explanation for the tiny observed differences between SNe IIb and Ib (Elmhamdi et al. 2006; Chornock et al. 2010), as in the Binary #2 scenario. The initial masses corresponding to SNe Ib (and SNe Ibc-pec) would then be roughly 12–25 $M_{\odot}$. These are massive stars in binaries whose winds can get rid of the remaining H, but are not strong enough to fully remove the He envelope, probably because they are underluminous after RLOF. The SNe Ib progenitors likely correspond to a population of lower luminosity, early-type WN stars that are difficult to detect next to their overluminous mass-gainer companions. Perhaps these post-RLOF systems would appear as peculiar Be or B[e]-like stars (mainly due to their overluminous H-rich companions) in nearby galaxies, likely showing signs of asymmetric CSM.

(6) It retains the quality that SNe Ic will still trace the most massive stars, especially those at higher metallicity, whether they arise from binaries or single stars. It also gives two different channels for making SNe Ic, perhaps providing an avenue for explaining the diversity among SNe Ic (i.e. normal versus broad-lined SNe Ic). This is an important point beyond the scope of this paper, but Fig. 7 suggests some interesting possibilities. Even some broad-lined SNe Ic, however, appear to arise from only moderately massive stars,

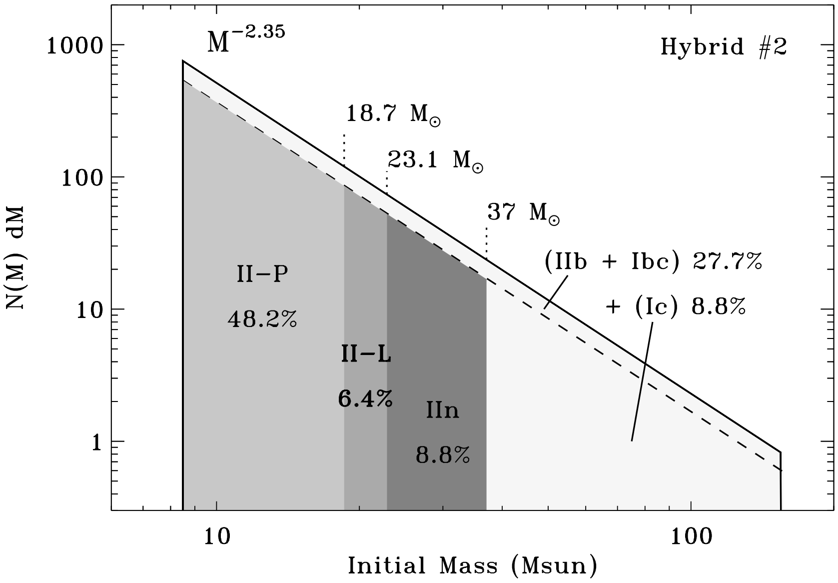

Figure 8. This is virtually the same as Fig. 7, except that the SNe IIn and single-star SNe Ic are not divided equally across the range of masses; instead, the SNe IIn occupy lower masses than single-star SNe Ic. For equal fractions, the dividing mass between SNe IIn and single-star SNe Ic would need to be $\sim$37 $M_{\odot}$.

based on the ejecta mass estimates and progenitor limits (Iwamoto et al. 1994; Mazzali et al. 2002; Sauer et al. 2006; Crockett et al. 2007).

(7) SNe Ib, on the other hand, do not trace the highest-mass stars or regions of high metallicity quite as well in this scenario, since it is probably the lower-mass stars or lower-metallicity stars that fail to drive away their He envelopes. This scenario would predict noticeable differences between the environments and progenitors of SNe Ib and Ic, with SNe Ic tending to trace higher initial mass and higher metallicity. There is some empirical support for this (Kelly et al. 2008; Anderson & James 2009; Papers I and II), but further study should treat SNe Ib and Ic separately.

(8) SNe Ib are less common and there are fewer well-studied examples compared to SNe Ic, but a recent detailed investigation of the SN Ib 2007Y revealed a small ejecta mass that suggested a low initial mass of only 10–13 $M_\odot$ for the progenitor, and interestingly, deduced a progenitor mass-loss rate of only $\lesssim 10^{-6}$ $M_\odot$ (Stritzinger et al. 2009). This mass-loss rate derived from radio and X-ray data is quite low compared to mass-loss rates of classical WR stars, supporting the idea that SNe Ib arise from lower-mass stars than classical WR stars, and that they have relatively low luminosity and weak winds (see also Filippenko 1991). It is even possible, for instance, that the wind of the mass-gainer companion (e.g. an OB supergiant) will be stronger than the wind of the SN Ib progenitor star, and that the SN blast wave will interact mostly with its companion's wind. Whether or not the wind is H-poor is difficult to ascertain from radio or X-ray observations, and deriving a progenitor mass-loss rate depends also on an assumed wind velocity (i.e. it may be significantly lower for a slow B-supergiant wind than for a fast WR wind).

(9) There may be a regime where SNe Ic and SNe IIn overlap, coming from the transition between very massive single stars that are successful in shedding their H envelopes through LBV eruptions (Smith & Owocki 2006) and those that cannot. This may depend on initial rotation or metallicity, and we speculate that the transition may be the origin of some of the unusual 'hybrid' SNe that have been classified as Type Ia/IIn, such as SNe 2002ic, 2005gj, 1997cy and 1999E (Germany et al. 2000; Turatto et al. 2000; Hamuy et al. 2003; Rigon et al. 2003; Wood-Vasey, Wang & Aldering 2004; Chugai & Yungelson 2004; Kotak et al. 2004; Wang et al. 2004; Aldering et al. 2006; Benetti et al. 2006; Chugai & Chevalier 2006; Prieto et al. 2007). Benetti et al. (2006) have argued that these may in fact be SNe Ic that appear as SNe IIn because of CSM interaction, rather than SNe Ia; this point is speculative and still debated, however. We conjecture that unusual SNe Ibn like SN 2006jc (e.g. Foley et al. 2007; Pastorello et al. 2007) may fit in a similar transitional category of very massive stars.

All things considered, we favour a hybrid scenario like Fig. 7 as the basic explanation for the observed fractions of various SN types in large galaxies, invoking binary RLOF to account for most SNe IIb, Ib and some Ic, and yet retaining single-star mass-loss with increasing mass to account for SNe II-P, II-L, IIn and some Ic in the most extreme cases. We stress, however, that this is hypothetical, with specific binary fractions and other parameters adopted to encapsulate only the broad properties of various SN types. Fig. 7 adopted a constant fraction of progenitors that go through RLOF, whereas this may obviously depend on initial mass, and RLOF efficiency may depend on other factors like binary separation and metallicity. Thus, the mass divisions between various types are meant as a general guide, rather than definitive values. This is certainly an oversimplification, and there may well be exceptions for individual cases or extreme conditions. More study is needed, including detailed population synthesis models with both binary evolution and LBV-like mass-loss for massive stars. The binary fraction and its variation with initial mass are key parameters, as is the behaviour of wind and eruptive mass-loss with metallicity and rotation. However, we hope that keeping a scenario such as Fig. 7 in mind will be useful to guide intuition for mapping SNe to stellar initial masses.

5 CONSEQUENCES AND FUTURE TESTS

If SNe IIb really result from a different channel than other SNe II, a simple comparison of the relative numbers of SNe Ibc and SNe II (including SN IIb with other SNe II) is probably misleading. Such a comparison would make sense in the standard single-star scenario where all stars above some threshold mass, M_{WR}, make WR stars and SNe Ibc (Fig. 4), but we have argued that this simple hypothesis is contradicted by SN observations. Instead, an analysis that retains SN types in-line with the separate binary and single-star channels discussed here would be more appropriate. For example, whereas envelope stripping via binary RLOF should not necessarily depend on metallicity or initial mass (unless the close binary fraction changes with mass), the transition SN IIb → Ib → Ic is caused directly by the line-driven wind of the post-RLOF WR-like star (i.e. proceeding from a low-luminosity WN with some H, to a normal WN, to WC). We should therefore be very interested to see how fractions of these *subtypes* change with metallicity.

Thus, previous studies that have compared the ratio $N_{\mathrm{Ibc}}/N_{\mathrm{II}}$, lumping SNe IIb together with other SNe II, may produce somewhat misleading trends and may inspire erroneous conclusions. In future studies, as larger numbers of all types of SNe become available, it will be useful to compare relative numbers of individual subtypes (IIb:Ib:Ic) as well as the ratio of larger groups that represent different channels [e.g. (IIb + Ib + Ic) / (II-P + II-L + IIn)] with metallicity and host-galaxy environment. The properties of SN II environments would be particularly interesting; the Binary #2 or hybrid hypotheses would predict, for example, that SNe IIn come from more massive stars and should therefore trace clusters and H II regions to a higher degree than SNe II-P and II-L. This would not be so noticeable for the single-star scenario shown in Fig. 4. We would not necessarily expect, however, that SNe IIn would be concentrated in galaxy centres, as that may betray a high-metallicity effect, which leads instead to SNe Ic for the most massive stars. Very massive stars that retain their H envelopes until shortly before core collapse might instead favour lower metallicity, and hence smaller host galaxies. This does indeed seem to be the case, as we point out in Paper II.

A central hypothesis is that SNe Ib trace a population of moderately massive stars that have lost their H envelopes primarily via binary RLOF. These progenitors are like classical WR stars in that they are H deficient, but they differ in that they are likely to be underluminous with relatively weak winds, and stem from a lower range of initial masses of roughly 12–25 $M_\odot$. These may not be recognized as WR stars because of their weaker winds and less prominent emission lines (see also Filippenko 1991). In nearby stellar populations, the SN Ib progenitors may be among the group of underluminous early WN stars, or they may reside in binary systems where they are hard to detect next to their overluminous mass-gainer companions. We have speculated that these post-RLOF systems of moderate mass may appear as Be, B[e], or LBV-like stars, perhaps with asymmetric CSM. Other potential SN Ib or Ic progenitor systems are famous WR+OB systems like V444 Cygni, γ^2 Vel or RY Sct.

Although SNe Ib are relatively rare, it will be important to distinguish SNe Ib from Ic in future analyses, and to clarify their different properties as well as any range in parameter space where they may overlap. It will be especially important to further clarify the residual He surface mass that separates SNe Ib from Ic; there may obviously be examples of a smooth transition in He mass between them. If SNe Ib arise from RLOF in binary systems, then the mass-loss rates of the progenitor stars derived from radio and X-ray observations may be tricky to interpret. For example, we noted that the wind of the overluminous mass-gainer companion may be stronger than the SN progenitor star itself, and so interaction between the SN blast wave and the companion's wind might dominate the observed radio and X-ray emission. Without a radiative shock to produce strong Balmer lines, it would be difficult to determine whether the wind is deficient in hydrogen.[8]

Lastly, it would be interesting to further investigate differences among environments and progenitors of SNe Ic, since this class alone makes up 15 per cent of all CCSNe (a substantial fraction of the most massive stars), and may have multiple progenitor channels. Do the broad-lined SNe Ic arise preferentially from one channel? This is a key question in regard to the progenitors of long-duration gamma-ray bursts.

6 CONCLUSIONS

We have studied the observed fractions of different SN types from LOSS, and considered the implications for massive star evolution. Assuming a Salpeter IMF, we have examined what ranges of initial mass are needed to account for the observed fractions of SNe II-P, II-L, IIn, IIb, Ib and Ic under various assumptions about the roles of stellar winds and close binary RLOF in stellar evolution. We briefly list the main conclusions here, which apply to stellar evolution in relatively large galaxies.

(1) A major finding is that the high observed fraction of SNe Ibc cannot be reconciled with predictions of single-star evolution, where a star's own wind dominates the removal of its H envelope. The initial-mass range corresponding to the observed population of classical WR stars can only account for about half of the observed SNe Ibc, so classical WR stars are not the progenitors of a significant fraction of SNe Ibc. Similarly, the initial mass above which single stars are expected to shed their own envelopes provides a vastly insufficient fraction of stripped-envelope progenitors, even with the overly generous mass-loss rates adopted in most stellar evolution models.

(2) Instead, we find it likely that RLOF in binary systems is responsible for the stripped-envelope progenitors of most SNe IIb and Ib, and probably a large fraction of SNe Ic as well. If these are distributed over the full range of masses, then SNe IIb and Ib probably arise from lower initial masses of 8.5–25 $M_{\odot}$, and SNe Ic arise from more massive stars with stronger winds.

(3) Even if binary RLOF dominates the removal of the H envelope, the further removal of the He layer depends on metallicity-dependent line-driven winds of the WR star, so SNe Ic are still expected to favour more luminous stars and higher-metallicity environments.

(4) If the progenitors of SNe Ib and IIb are not classical WR stars because their initial masses are too low, then what kind of stars are the progenitors? We conjecture that they are probably underluminous H-poor stars with weak winds that would not necessarily be recognized as WR stars with prominent emission-line spectra. They may be easily hidden by their overluminous mass-gainer companions, which may in some cases appear as B[e] supergiants or related stars with asymmetric CSM. If so, one must be cautious when interpreting signatures of the CSM interaction in SNe Ib, as the emission may in some cases be dominated by SN shock interaction with a companion star's wind.

(5) If binary RLOF is important in producing stripped-envelope progenitors that are a substantial fraction (1/4 to 1/3) of all SN progenitors, then it would be a mistake to use statistics of SN types or WR/O-star ratios to guide models for single-star evolution.

(6) After shifting most stripped-envelope progenitors to the binary RLOF channel, the progenitors of the remaining SN types (H-rich single stars, wide binaries and possibly mass gainers in RLOF binaries) must be redistributed across the full range of initial masses. In our favoured scenario (Fig. 7), SNe II-P correspond to initial masses of roughly 8.5–18 $M_{\odot}$, SNe II-L to 18–23 $M_{\odot}$ and SNe IIn to 23–150 $M_{\odot}$. This produces a good agreement with mass ranges inferred from progenitor studies of SNe II-P, II-L and IIn. In particular, this allows some SNe IIn to arise from among the most massive stars, as suggested by some very luminous SNe IIn. Most stellar evolution models fail to account for very massive stars reaching core collapse without shedding their H envelope, but this is an expected outcome of the lower mass-loss rates now confirmed by observations. We also find it likely that some fraction of the most massive single stars shed their H envelopes to produce WR stars and SNe Ic, probably due to high metallicity. This allows for the possibility that SNe IIn favour low-metallicity environments.

(7) We briefly consider the possibility that some massive stars collapse directly to BHs without a visible SN display. We can rule out this option for the scenario of standard single-star evolution, because it would make all the problems we note with Fig. 4 worse. We find no empirical support for the argument that the 'RSG problem' may imply direct SN-less BH formation, because this problem largely goes away with more reliable SN subtype fractions and with the realization that some RSG stars evolve to other types of progenitors before exploding. Though we cannot rule out the possibility that some massive single stars within a particular mass range suffer quiet collapse to a BH in a binary-dominated scenario, quiet BH collapse is not required to explain the observed relative fractions of CCSNe.

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[8] In the special case of SN 2006jc, the dense CSM produced strong He I lines, so one can infer that the progenitor star suffered a precursor eruption and that the CSM was not from a companion (Foley et al. 2007; Pastorello et al. 2007; Smith et al. 2008a); other cases of SNe Ib are less clear.

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