Supernovae and their Progenitors

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Abstract. The physics of supernova explosions and essential aspects of the progenitor evolution are discussed for both hydrodynamic (core collapse) and thermonuclear powered events. Sufficient information is given for non-specialists in the field to judge the reliability of the various predictions of current models and to apply the most recent results to studies of Galactic evolution.

1. Introduction

Supernovae (SNe) are short lived, local events in galaxies. Their energy is generated in, at most, a few seconds, though the optical display has a time scale of order months, during which time photons having a total energy 10^{48} - 10^{49} erg are emitted. Therefore, at a typical event rate of $\sim$0.03 SNe/yr (van den Bergh & Tammann 1991), SNe do not contribute appreciably to the integrated light of normal galaxies (cf., however, Terlevich et al. 1992). The kinetic energy of a typical SN (of either type) is a factor of 100 larger, i.e., $\sim 10^{51}$ erg. This leads, for the same SN-rate, to an average energy input of $\sim 3\,10^8 L_\odot$, a significant fraction of a galactic luminosity. Due to the interaction of the SN remnants with the ISM, a large fraction of the kinetic energy may be converted into photons (McKee & Truelove 1995). Therefore, at certain wavelengths the radiation of some galaxies may even be dominated by the contribution from SN remnants, e.g., in the radio regime (Condon 1992).

Indeed, because of the large amount of kinetic energy produced by SNe, their impact on the dynamical and thermal state of the ISM is considerable. For the above SN-rate, it takes only $\sim 10^7$ yr for SNe to produce an amount of kinetic energy equivalent to the potential energy of the (luminous part of the) galaxy. In particular, SNe from massive stars that explode in young associations can act, together with neighboring explosions and with the equally important contribution of massive star winds, to form galactic superbubbles (e.g., Chu & Kennicutt 1994) and galactic winds (Leitherer et al. 1992). Finally, the chemical evolution of galaxies, which is intimately coupled to the thermal and dynamical

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evolution of their ISM, is largely dominated by the production and ejection of heavy elements by SNe and their progenitors (e.g., Timmes et al. 1995).

Two major mechanisms have been identified for SN explosions. One is the collapse of an iron core (or in rare instances a neon-oxygen core) of about the Chandrasekhar mass in the center of a massive star. The collapse to a neutron star releases a flood of neutrinos which blows a bubble of radiation around the core which in turn drives a shock out through the star. The second mechanism is the thermonuclear explosion of an accreting C/O white dwarf (WD). Though both mechanisms lead to the hydrodynamic ejection of mass and involve thermonuclear burning, we designate events based upon the first mechanism as hydrodynamic SNe (Sect. 2), and those from the second as thermonuclear SNe (Sect. 3). The discussion of mass loss processes in SN progenitors from single stars (Sect. 4) and binary systems (Sect. 5) will illuminate the fact that these two SN mechanisms do not simply coincide with the observationally defined Type II and Type I SN classes. Some conclusions for chemical evolution models are given in Sect. 6.

2. Hydrodynamic Supernovae

Whether a single star will end it life as a SN depends primarily upon its initial mass. $M > M_{SN} \simeq 8M_\odot$ is generally thought to be required to ignite carbon and proceed to the advanced burning stages that lead to core collapse. This limiting value depends however upon how convection is modeled during hydrogen and helium burning. Overshoot mixing, for example, gives larger C/O-core masses for a given initial mass, and thus smaller values for M_{SN} (e.g., Bertelli et al. 1985). The star's metallicity, Z, is also relevant in this context (cf. Vassiliadis & Wood 1993), since smaller Z may reduce the mass loss on the asymptotic giant branch (AGB) and allow the stellar core to grow beyond the Chandrasekhar mass. It cannot be excluded that some single stars in a narrow initial mass range around $8M_\odot$ form strongly degenerate C/O-cores which grow above the Chandrasekhar mass due to shell burning and then experience a thermonuclear explosion (Sect. 3). Unless they have lost most of their envelope, these would be difficult to distinguish from ordinary SNe that occur in red supergiants, except that their light curves would have a very pronounced tail from radioactive decay (Woosley & Iben 1988). Single stars well below $\sim 8M_\odot$ are thought to lose their H-rich envelope on the AGB and to evolve into WD's; compelling evidence for this being the presence of WD's in young clusters with a main sequence (MS) turn-off mass of $\sim 5M_\odot$ (Weidemann 1990).

The collapse of a metal-rich stellar core — iron for stars heavier than about 10 $M_\odot$, neon and oxygen for stars around 9 $M_\odot$ — starts when electron capture (for stars less than about 15 $M_\odot$) and photodisintegration (for heavier stars) begin to remove the pressure necessary for a stable structure. The breakdown of iron by the photon bath only proceeds part way to alpha-particles as the large partition function of heavy bound nuclei in equilibrium guarantees they are always the dominant constituent. Electron capture accelerates as the matter goes to higher density resulting in a distribution of nuclei that is increasingly neutron rich. At about 5×10^{11} g cm^{-3}, neutrinos become trapped and must diffuse out of the core. The collapse is only halted by a sudden increase of the adiabatic index of matter when it reaches and passes the density of the atomic nucleus, about 2.4×10^{14} g cm^{-3}. During the so called "bounce", the density rises to several times this value and then rebounds like a coiled spring. About half way out in the collapsing core a shock forms where this rebounding matter meets the infalling matter supersonically.

During the last decade, it has become clear that this bounce shock cannot explode the star. For iron cores above about 1.1 $M_\odot$, which includes all pre-SN models ever calculated, it loses too much energy to photodisintegration and neutrinos. The shock loses all outward velocity while still well within the iron core and becomes a stalled accretion shock. A successful explosion then requires a new energy source. This is now known to be neutrino energy deposition (Colgate & White 1966; Bethe & Wilson 1985; Wilson & Mayle 1993). The shock wave is revived on a time $\sim$0.1 s, long compared to the hydro time scale, about 10 ms for the shock to reach the edge of the core, but short compared to the 3 - 10 s Kelvin-Helmholtz time scale for the neutron star to emit its binding energy. Considerable progress has been made in the last 4 years in simulating this event in two dimensions (Herant et al. 1992, 1994; Burrows et al. 1995; Janka & Müller 1996). Multi-dimensional calculations (or at least a parametric representation of multi-D effects) are necessary to see the convective flow that boosts the neutrino luminosity of the proto-neutron star, increases the efficiency of neutrino absorption, and carries the neutrino deposited energy out to the shock.

However, these calculations have only been done for a limited range of stellar masses (13 and 15 $M_\odot$), in two dimensions not three, and with very simple neutrino physics. They have a common problem in that they eject too much neutron-rich nucleosynthesis and in all calculations published so far, follow the explosion for a very limited time (a few tenths of a second). Thus it is still not known how the kinetic energy produced by hydrodynamic SNe depends on the initial stellar mass (or the iron core mass); whether there is some stellar mass above which the explosion fails; and where the separation between ejecta and collapsed remnant will occur in the final explosion.

This last point is particularly important with respect to both the light curve and nucleosynthesis. Woosley & Weaver (1995) have shown that the amount of mass that falls into the collapsed remnant is very sensitive to the explosion energy, e.g., whether it is 1×10^{51} erg or 2×10^{51} erg. In their (1D) calculations many SNe leave black holes formed a few hours after launching successful shocks that make bright optical SNe. In some cases the radioactive ^{56}Ni falls back which removes its contribution to the light curve and nucleosynthesis. In others, the entire heavy element core implodes.

This uncertainty in both the launching of a successful shock and the amount of mass that falls back plagues chiefly the very massive stars, $M \gtrsim 25\ M_\odot$, which may be relatively rare events, both because such stars form infrequently and because above 30 $M_\odot$, mass loss becomes very important and may reduce the final helium core mass. Thus the principal effect is upon the nucleosynthesis, especially of oxygen, iron, and the ratio of helium to heavy elements (dY/dZ). For the common SNe below 25 $M_\odot$, typical amounts of ^{56}Ni ejected in the models of Woosley & Weaver (1995) are consistent with the empirical values of

$0.07 \pm 0.01 M_{\odot}$ for SN 1987A (Arnett et al. 1989) and 0.08 ± 0.02 for SN 1993J (Woosley et al 1994; Shigeyama et al. 1994).

3. Thermonuclear Supernovae

Thermonuclear SNe draw their energy from thermonuclear fusion and as such can be considered as stellar mass bombs. In order to avoid the moderating effect of gravothermal expansion, which limits the nuclear burning in normal stars to thermal equilibrium, the burning matter needs to be highly degenerate. This is the case for the central regions of a C/O-WD near the Chandrasekhar mass (1.39 $M_{\odot}$), or, in some other models we shall discuss, for the base of the helium layer on a C/O-core of 0.6 to 0.9 $M_{\odot}$.

WD's which develop from single stars (i.e. with initial mass $< M_{SN}$; Sect. 2) simply fade and cool and will never explode. However, WD's in binary systems may experience mass accretion and may thus have a mass increasing with time. Though helium WD's may form and also explode due to mass transfer in some close binary systems, and O/Ne/Mg WD's are known to exist, neither can give an explosion resembling the common Type Ia event. Helium core detonations expand too rapidly and produce inadequate amounts of intermediate mass elements (Woosley et al. 1986). Neon cores experience accretion induced collapse to neutron stars (Saio & Nomoto, 1985; Woosley & Weaver 1986; Timmes & Woosley 1992).

At present, there may be two ways to explode an accreting C/O-WD. One way, which is more in line with classical thinking on the subject (e.g., Arnett 1969) is that the rate of accretion of hydrogen is rather high (i.e. $\dot{M} \sim 10^{-7} M_{\odot}\, yr^{-1}$ so that the nova instability is avoided and the WD can grow. Once the critical mass is attained ($\sim 1.39 M_{\odot}$), highly screened carbon fusion generates energy faster than plasma neutrinos can carry it away and a runaway develops. For thousands of years the excess energy generated deep in the star is carried away by convection, but eventually the runaway becomes so violent that a hydrodynamic response occurs. The other current Type Ia SN candidate becomes first unstable in the helium shell, prior to achieving the Chandrasekhar mass. The accretion rate needs to be near 3×10^{-8} $M_{\odot} yr^{-1}$, but this may be natural in systems merging by gravitational radiation. The accreted material needs to be helium to avoid the nova instability. For these conditions, the accreted helium will explode in a detonation which sends a strong sound wave into the C/O-core which may lead to the ignition of carbon. Carbon detonation then explodes the rest of the WD and light curves and nucleosynthesis like those needed for Type Ia SNe are obtained (Woosley & Weaver 1994a).

Multi-dimensional physical effects greatly complicate the numerical simulation of the explosions in both scenarios and make the outcome uncertain. For the Chandrasekhar mass models, once carbon burning has become dynamic, a highly localized thin sheet of burning (a "flame") forms. The rate of combustion depends upon what highly deformed topology this sheet assumes. It is deformed by the Rayleigh-Taylor instability, by turbulence, by shear mixing, and by other hydrodynamic instabilities (e.g., Niemeyer 1995; Niemeyer & Woosley 1996). Multi-dimensional calculations are just beginning to include this complexity, but much of the flame deformation remains below the resolution of achievable calculations. Thus prescriptions for “sub-grid turbulence” (Niemeyer & Hillebrandt 1995) and “fractal flames” (Woosley 1990) are adopted.

So far it is generally agreed that the carbon does not detonate promptly but burns, at least for a time, as a subsonic wrinkled flame, loosely referred to as a deflagration. However, calculations suggest that the persistence of such burning does not lead to an energetic explosion (e.g., Niemeyer 1995), at least not during the first pulse of expansion. So, by various contrivances, different groups force an acceleration of the flame at late times so as to burn a large fraction, but not all of the WD to ^{56}Ni. Khokhlov (1991abc) and Woosley & Weaver (1994b) cause the flame to make a transition to a detonation in the so called “delayed detonation” model. Others (Khokhlov 1991b; Arnett & Livne 1994ab; Woosley 1996) allow the SN to make one or more pulses in which hot ash and cold fuel become intermingled and then to detonate – the “pulsational detonation model”. These late time detonation models are particularly good at representing the light curves and spectra actually observed in Type Ia SNe (Höflich & Khokhlov 1996).

In the sub-Chandrasekhar mass models there are also appreciable uncertainties regarding the multi-dimensional nature of the explosion. Here it is agreed that the mode of burning is detonation, but authors disagree on whether the detonation of the helium shell is able to provoke a detonation in the carbon. Calculations in one dimension (Woosley & Weaver 1994b) give unambiguous explosions, but the center of the star is a singularity in these calculations. Two dimensional calculations by Livne & Glasner (1991) and Livne & Arnett (1996) also give carbon detonation, but the carbon ignites on the far side of the core from where the helium ignites and the ignition is not particularly robust. Three dimensional calculations by Benz (1996) and Garcia-Senz et al. (1996) do not show carbon detonation, unless the helium is ignited well away from the carbon-helium interface. For now, the issue is unresolved. Thus there are either a lot of these kinds of SNe or none. Explosion of the helium layer alone would give a fast UV-transient, not a Type Ia SN.

Though Chandrasekhar and sub-Chandrasekhar mass models for Type Ia SNe both involve exploding C/O-WD’s, some of their properties should be significantly different. Despite starting with a constant mass WD, the Chandrasekhar mass explosions could vary considerably one to the other depending on details of how and where the flame is ignited (Garcia-Senz & Woosley 1995), the carbon to oxygen ratio, the accretion rate, and the metallicity. However one expects in general that the sub-Chandrasekhar mass explosions will make less ^{56}Ni (at least in the CO-core) and be fainter at peak. As for Type Ib/c SNe (Sect. 4), deciding the correct model for Type Ia explosions may eventually occur by comparing the observed and predicted spectral evolution. Besides the fact that the number of observationally well studied Ia SNe is small, calculations of spectra of Ia models are complicated by non-LTE effects and the effects of mixing and clumping in the explosion. At present, models which fit the spectral evolution of observed Ia SNe all resemble in composition and velocity distribution the Chandrasekhar mass model ”W7” of Nomoto et al. (1984) which predicts the ejection of $\sim 0.6 M_\odot$ ^{56}Ni.

4. Progenitors: Single Stars

At the low mass end of the initial mass spectrum of single star SN progenitors, the possibility of a thermonuclear rather than hydrodynamical SN has already been discussed (Sect. 2). At the high mass end, core collapse may also be avoided in some cases. C/O-cores more massive than $\sim 50M_{\odot}$ collapse due to $e^{\pm}$-pair production with the possible subsequent disruption of the star by explosive oxygen burning (e.g., Woosley 1986). This scenario may occur for stars with an initial mass $M \gtrsim 100M_{\odot}$ (cf. Langer & El Eid 1986, El Eid & Langer 1986). However, it is likely to be restricted to low metallicities, since mass loss during hydrogen and helium burning will reduce the stellar mass to values well below $60M_{\odot}$ for any initial mass at solar metallicity (see below). The limiting metallicity below which pair formation SNe may occur is not well known due to a lack of the understanding of the physics of mass loss in the post-MS stages; according to Schaller et al. (1992) and Meynet et al. (1994), the transition may be roughly at $Z/Z_{\odot} \simeq 1/20$. Since the stellar IMF in the early universe is also poorly determined, one cannot exclude an important role for pair formation SNe, even more so since stars in the initial mass range $\sim 30 - 100M_{\odot}$, which may contribute to the Galactic nucleosynthesis today due to efficient stellar wind mass loss, may form black holes at small metallicity.

For massive stars today, mass loss is clearly important. O and B stars have radiation driven winds which are theoretically well understood (cf. Lamers, this volume) and do not represent a major source of uncertainty for stellar evolution models. However, massive stars are supposed to lose most of their mass during the post-MS evolution, i.e. as red supergiants for $M \lesssim 35M_{\odot}$, and as Luminous Blue Variables (LBVs) or Wolf-Rayet stars for higher masses. For all these post-MS stages, we have neither reliable empirical mass loss rates nor quantitative mass loss theories.

However, significant constraints on the post-MS mass loss come from the distribution of luminous stars in the HR diagram. First, the absence of luminous red supergiants (with $\log L/L_{\odot} > 5.7$; Humphreys & Davidson 1979) can only be reconciled with stellar models assuming that correspondingly massive stars ($M \gtrsim 50M_{\odot}$) lose most of their H-rich envelope before core He-ignition. The idea that they do so as LBV's at the Humphreys-Davidson (1979) limit — the location of the observed, highly unstable LBV's, which apparently all have ejected circumstellar nebulae (Nota et al. 1995) — results, for a given stellar model, directly in a mass loss rate (Langer 1989a). Second, the large number of relatively faint ($\log L/L_{\odot} \simeq 4.5...5.0$) Wolf-Rayet stars (Hamann et al. 1995), which, due to a very narrow mass-luminosity relation for those objects (Maeder 1983, Langer 1989b), indicates a mass in the range $\sim 5...8M_{\odot}$ for them, as well as the large number of WC-type stars (which show core helium burning products at their *surface*), imply a very large amount of mass loss in the WR stage (Langer 1989c).

In fact, all Galactic stars initially more massive than $\sim 35M_{\odot}$ are thought to end their lives as hydrogen-free objects of roughly $5M_{\odot}$ (Schaller et al. 1992, Woosley et al. 1993, Meynet et al. 1994). This not only prevents the very massive stars ($M \gtrsim 100M_{\odot}$) from exploding through the pair formation mechanism, but also limits the mass of the iron core produced at the end of their thermonuclear evolution to values below $\sim 2M_\odot$ (Woosley et al. 1993) which drastically increases the probability for a successful hydrodynamic SN explosion compared with the situation without mass loss. Due to the lack of hydrogen, those would be classified as Type I SNe, and the theoretical light curves (Woosley et al. 1993) and spectra (Woosley & Eastman 1996; Eastman & Woosley, in prep.) may correspond well to some observed Type Ib/c events.

Due to the increased efficiency of mass loss for higher initial masses, the most massive iron cores in solar metallicity stars may actually be produced at $M \simeq 30M_\odot$, which makes the probability of black hole formation largest for initial masses around this value (cf. Maeder 1992; Woosley & Weaver 1995).

As indicated above, at low metallicity the situation may be quite different. Clearly, the metal line driven O and B star winds have a largely reduced efficiency (cf. Leitherer & Langer 1991); however, the metallicity dependence of LBV and WR star mass loss rates is unknown. The small number ratio of WR/O-stars in the SMC compared to the solar neighborhood (cf. Maeder & Conti 1994) may indicate that as $Z \to 0$ even the most massive stars evolve essentially without mass loss. An increasing number of observed nucleosynthesis patterns in extremely young galaxies — many of them are reported in these proceedings — may soon allow the testing of this scenario.

Finally, it should be noted that Galactic single stars in the initial mass range $8M_\odot \lesssim M \lesssim 25M_\odot$ very likely explode as red supergiants (cf. Schaller et al. 1992), which corresponds to the Type IIP subclass of hydrogen-rich SNe (Eastman et al. 1994). The effect of H-rich single star blue supergiant SN progenitors — as in the case of SN 1987A — appears to be restricted to low metallicities (cf. Langer 1991). However, the limiting metallicity below which blue supergiant explosions from single stars generally occur — which is certainly larger than zero — can not yet be precisely determined due to our insufficient knowledge of internal mixing processes during the early phases of massive star evolution (Langer & Maeder 1995, Fliegner et al. 1996)

5. Progenitors: Binaries

When studying SNe, the importance of binary progenitors is evident. For thermonuclear SNe binary models are inevitable (Sect. 3). However, many of the SN types associated with hydrodynamic events also seem to require binary models, though we should note that massive binaries may be less important at low metallicity where they are less likely to evolve into red supergiants (Sect. 4).

The primaries, i.e. the initially more massive stars in the systems, evolve faster and expand first. Therefore, the principal effect of the companion star on the primary is a largely increased mass loss. That is, primaries of any initial mass may evolve into hydrogen-poor stars, while for single star SN progenitors this is only true for $M \gtrsim 30M_\odot$. Expressed in order of an increasing fraction of the primary star mass lost to the binary companion, the following hydrodynamic SN events may be explained by close binary models (e.g., Branch et al. 1991): Type IIL, Type IIb, and Type Ib/c. The physical reason is that when the mass of the H-rich envelope is strongly reduced in a SN progenitor, it can no longer produce the plateau in the light curve of the exploding SN seen in Type IIPs. Instead the luminosity decays roughly exponentially (i.e. linear in the $\log L$ vs.

time diagram). For a further decreased H-envelope mass, the hydrogen lines in the SN spectrum — i.e. the Type II signature — may disappear a few weeks after the SN outburst (Type IIb like SN 1993J; i.e. a Type II evolves into a Type Ib), while a complete loss of the H-rich envelope and part of the helium mantle leads to a Type I classification right away (Ib/c).

One should note, however, that none of the SN subtypes can be assigned uniquely to binary systems. The reason is, as outlined in Section 4, that massive single stars of increasing initial mass end their lives with increased amounts of mass loss. For example, the sequence Type IIP – Type IIL – Type IIb – Type Ib/c may correspond (at solar metallicity) also to single star progenitors of increasing initial mass (cf. Woosley et al. 1995). Furthermore, it has been shown by Langer (1995) that for initial masses $\gtrsim 40 M_\odot$, massive close binary components evolve essentially as if they were single stars. The relative fractions of single stars and binary systems in each of the spectral subclasses is not well known (cf. Podsiadlowski et al. 1992); however, the frequency ratio of Type Ib/c vs. Type IIP SNe appears to be too large in order to allow the interpretation of the majority of Type Ib/c events as due to hydrogen-free single stars — which would be Wolf-Rayet stars and thus correspond to initial masses $M \gtrsim 30 M_\odot$. Furthermore, the detailed analysis of nearby SNe, in particular the Type IIb SN 1993J, results in arguments in favor of a relatively small progenitor mass ($15 - 20 M_\odot$ in this case; Nomoto et al. 1993, Woosley et al. 1994), which, as a single star, would probably have exploded as a Type IIP SN.

The secondary star of a massive close binary system — i.e. the mass gainer — is also likely to evolve into a SN explosion. Whether or not its structure would be peculiar has been recently analyzed by Braun & Langer (1995) for the most frequent case of the mass transfer occurring during the MS phase of the secondary. The answer was found to depend critically upon still unknown properties of convection, with the possibility of a high fraction of secondaries ending up with much too small helium cores, compared to single stars of the same mass as the secondaries after accretion. This mechanism leads to blue rather than red supergiant SN progenitors, and it has been proposed earlier for accretion during H-shell burning (Podsiadlowski & Joss 1989, de Loore & Vanbeveren 1992) to account for SN 1987A. However, since accretion during core H-burning is much more common, the model of Braun & Langer (1995) predicts much more — very subluminous — explosions à la SN 1987A, at all metallicities.

In very close systems, one may also expect a common envelope scenario, with a major part of the H-rich envelope of the primary leaving the binary system. Then, both stars may merge, leading to a H-rich SN progenitor with an envelope which is strongly enriched in H-burning products. Or, both stars remain separated but very close, and the secondary will, after core H-exhaustion, expand and produce a second Roche-lobe overflow, leading to structures which have been discussed for massive primaries above (cf. Podsiadlowski et al. 1992).

Finally, one should mention the still tentative identifications which are discussed for the progenitors of Type Ia SNe (cf. also Branch et al. 1995). All involve close binary evolution, and in particular the accretion of matter onto a C/O-WD (Sect. 3). Observational counterparts of the Chandrasekhar mass progenitors may be the recently discovered “supersoft” x-ray sources (Van den

Heuvel et al. 1992; Rappaport et al. 1994). It is not clear at the present time whether there are adequate numbers of such objects, whether there are *any* in elliptical galaxies where Type Ia SNe also occur, or whether the necessary accretion rate can be maintained sufficiently long for the WD to grow to 1.39 $M_\odot$, but still it is encouraging that *any* counterpart exists. For the sub-Chandrasekhar mass systems, potential counterparts are symbiotic systems, helium star cataclysmic variables (Iben & Tutukov 1991; Limongi & Tornambe 1991; Kenyon et al. 1993; Munari & Renzini 1992) and possibly other cataclysmic like systems (Canal et al. 1996).

6. Conclusions: a recipe for chemical evolution

What is the "recipe" to obtain the galactic chemical mix? There are as many answers as there are chefs and that's a lot. We conclude with our own favorite.

First, start with the Big Bang; this gives ^{1,2}H, most ^{3,4}He and some ^{7}Li (e.g., Walker et al. 1991). Add the contributions of the massive single stars (Woosley & Weaver 1995), with an upper mass cut off at, say, $30M_\odot$ at low Z, assuming black holes are produced above that, and ignoring pair formation supernovae. At high Z, i.e. for $Z \gtrsim 0.1 Z_\odot$, stars initially more massive than $\sim 40M_\odot$ lose so much mass due to stellar winds, that they can explode (as Type Ib/c SNe; Sect. 4) thereby boosting the production of carbon by mass loosing WC stars (Maeder 1992, Langer & Henkel 1995, Woosley et al. 1995). This leaves the initial mass range $30M_\odot \lesssim M \lesssim 40M_\odot$ for black hole formation at high metallicity.

Now add the Type Ib and Ic SNe coming from binary systems. This takes some art because their number ratio to Type II's will change with metallicity, since the number of interacting binaries will decrease at low Z (Sect. 5). Take the yields of Woosley et al. (1995) for those stars which become Type Ib or Ic. Because the mass of the pre-SN star does not change much for Type Ib/c's (at least the ones we see now), the yields don't change much either. Assume that, in addition to the single star Ib/c SN progenitors mentioned above, 1/3 of all stars that become red supergiants (more now than then) are in close binaries and become Ib/c SNe.

Now add the Type Ia's. W7 (Nomoto et al. 1984) is a good prototype for the nucleosynthesis in Chandrasekhar mass models (Sect. 3). Use Woosley & Weaver (1994a) for sub-Chandrasekhar mass models. Assume a ratio according to taste — 1 to 2 in favor of the Chandrasekhar mass models might be good. Let about 5% of these Ia models ignite at a density above 6×10^9 g cm^{-3} and make neutron-rich nuclei (Woosley & Eastman 1992). Add a trace of classical novae to get ^{15}N. And now come intermediate mass stars (e..g, Renzini & Voli 1981) to add to helium, ^{12}C, ^{13}C, ^{14}N, and other light isotopes. Very rare species, ^{6}Li, ^{9}Be, and ^{10}B, require cosmic rays (Prantzos et al. 1993). Zinc and some of the proton-rich nuclei above zinc up to mass 92 require a neutrino powered wind in hydrodynamic SNe (Hoffman et al 1996). This mixture should adequately describe the evolution of nuclei up to mass 100. Heavier nuclei come from the *s*-process in AGB stars (see, e.g., Gallino et al. 1993) and the *r*-process in hydrodynamical SNe (Woosley et al. 1994).

In this paper, we pointed out the many remaining uncertainties in the modeling of the heavy elements producing stars. One way to significantly reduce them is to constrain the nucleosynthesis processes and thereby massive star evolution in the early universe by abundance determinations at high redshift. We believe that the interaction between stellar and extragalactic research may be most fruitful in this field in the near future.

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