



Nucleosynthesis and remnants in massive stars of solar metallicity

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Abstract

Hans Bethe contributed in many ways to our understanding of the supernovae that happen in massive stars, but, to this day, a first principles model of how the explosion is energized is lacking. Nevertheless, a quantitative theory of nucleosynthesis is possible. We present a survey of the nucleosynthesis that occurs in 32 stars of solar metallicity in the mass range 12–120 M_{\odot} . The most recent set of solar abundances, opacities, mass loss rates, and current estimates of nuclear reaction rates are employed. Restrictions on the mass cut and explosion energy of the supernovae based upon nucleosynthesis, measured neutron star masses, and light curves are discussed and applied. The nucleosynthetic results, when integrated over a Salpeter initial mass function (IMF), agree quite well with what is seen in the sun. We discuss in some detail the production of the long lived radioactivities, ^{26}Al and ^{60}Fe , and why recent model-based estimates of the ratio $^{60}\text{Fe}/^{26}\text{Al}$ are overly large compared with what satellites have observed. A major source of the discrepancy is the uncertain nuclear cross sections for the creation and destruction of these unstable isotopes.

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1. Introduction

Starting in the late 1970s, with the encouragement of his good friend Gerry Brown, Hans Bethe became interested in applying his expertise in nuclear physics to one of the more vexing problems in modern astrophysics—how massive stars die as supernovae. The problem is difficult for a variety of reasons. The iron core of a massive star collapses to a neutron star (or sometimes a black hole) and, somehow, some fraction of that remnant’s binding energy is converted into outwards kinetic energy in the overlying star. The favored model, now as then, says that the binding energy of the neutron star is radiated as neutrinos, a fraction of which deposit their energy in the matter above the neutron star causing it to expand and explode (Colgate and White, 1966).

When Hans began to work on the problem, supernova models were not giving explosions. Moreover, the physics was very uncertain with bounce densities ranging from 10^{13} to 10^{15} g cm⁻³ (e.g., Wilson, 1978). The nuclear equation of state was particularly uncertain. A major breakthrough was the work by Bethe et al. (1979) who showed that the heat capacity of the nuclear bound states was much larger than previously believed (Fowler et al., 1978). In fact, the mean excitation energy was $E_x \sim (A/8)(kT)^2$ and the partition function associated with all these states was exponentially huge, $G \sim \exp((A/8)(kT))$. Consequently, nuclear equilibrium favored bound nuclei which remained abundant, increasing their average mass, until they touched and merged near nuclear density. Bounce occurred at super-nuclear density on the hard core, repulsive component of the strong force (not thermal pressure as some calculations claimed) and was at low entropy. The general idea of entropy as an important variable in core collapse came from Hans, who liked to remark that though the bounce was thermally very hot, in terms of entropy it was as ordered as ice.

During the next 20 years, Hans made many other lasting contributions to supernova theory, including the currently favored “delayed” neutrino transport paradigm in which convection plays a major role (Bethe and Wilson, 1985)¹ Hans also introduced the ideas of a “gain radius”, where neutrino heating first exceeds neutrino losses, and of “net ram”, the momentum of the accretion flux that must be overcome to get the shock to move out. He excelled in simple analytic models for the physics of core collapse, and brought a much needed physically intuitive understanding of a subject that had hitherto been largely numerical (e.g., Bethe, 1990).

Because of his historical interests in stellar structure and nuclear physics, Hans was also interested in the presupernova evolution of massive stars and in nucleosynthesis. During his visits to Santa Cruz and by mail, we had many discussions on the progenitor of SN 1987A, the physics of supernova light curves, the nature of the “reverse shock”, explosive nucleosynthesis, and on the *r*-process. Thus it is to his memory that this paper is dedicated.

To this day, we still don’t know exactly how massive stars explode (Woosley and Janka, 2005), so the parameterization of the explosion is discussed in Section 3. The key nuclear reaction rates and other uncertain aspects of the presupernova evolution are described in Section 2. In Section 4, our principal nucleosynthetic results are presented, and in Section 5, we conclude with a discussion of two key species of interest in γ -line astronomy, ²⁶Al and ⁶⁰Fe.

Throughout this paper and in the future, we employ a unit of energy, the “Bethe”, abbreviated “B”, equal to 1.0×10^{51} erg. Gerry Brown introduced, and Hans and Gerry both promoted the use of an alternate term, “foe”, frequently found in the supernova literature to stand for 10^{51} erg, but in deference to Hans’ contributions to the field, we follow the convention suggested by Weinberg (2006).

¹ The first calculation to show the revival of the shock by neutrino heating was carried out by Wilson alone in 1982 (Wilson, 1985), but analysis of the calculation and the first refereed publication was by Bethe and Wilson. For a time, Hans also embraced the idea of “prompt explosions” (Baron et al., 1987), explosions in which neutrino transport played no constructive role and the explosion was due to a hydrodynamical “bounce”. He gave up the idea after detailed calculations showed that neutrino losses and photodisintegration killed the prompt shock.

2. Uncertainties in the presupernova evolution

2.1. Critical reaction rates

The key uncertain reaction rate affecting both the structure of and nucleosynthesis in massive stars remains $^{12}\text{C}(\alpha, \gamma)^{16}\text{O}$, despite over 30 years of painstaking laboratory investigation (e.g., Dyer and Barnes, 1974). The experimental situation was recently reviewed by Buchmann (2005), who recommends $S(300\text{ keV}) = 102\text{--}198\text{ keV b}$ with a best value of 145 keV b . Based upon nucleosynthesis considerations, Weaver and Woosley (1993) estimated an S -factor of $\sim 170\text{ keV b}$, which remains within the experimental range today. More precisely, Weaver and Woosley suggested a rate 1.7 ± 0.5 times that of Caughlan and Fowler (1988), which would be $120\text{--}220\text{ keV b}$, but even at the time, the error bar was regarded as liberal. More recently, Boyse et al. (2002) has revised the nucleosynthesis constraints using more stellar models, a finer grid of $^{12}\text{C}(\alpha, \gamma)^{16}\text{O}$ rates, finer stellar zoning, and other improvements to the stellar model. Their results, shown in Fig. 1, are in good agreement with the earlier calculations of Weaver and Woosley, but give a narrower error bar and also make the sensitivity of the results to this rate (variations of only 10% matter) more apparent. Because of the need to include a rate that is accurate across a wide range of temperature, not just during helium burning, the preferred rate is again expressed as a multiple of a published rate fit, this time Buchmann (1996, 1997), which has $S(300\text{ keV}) = 146\text{ keV b}$. Boyes' best fit is about 1.2 times this, or 175 keV b and a value of

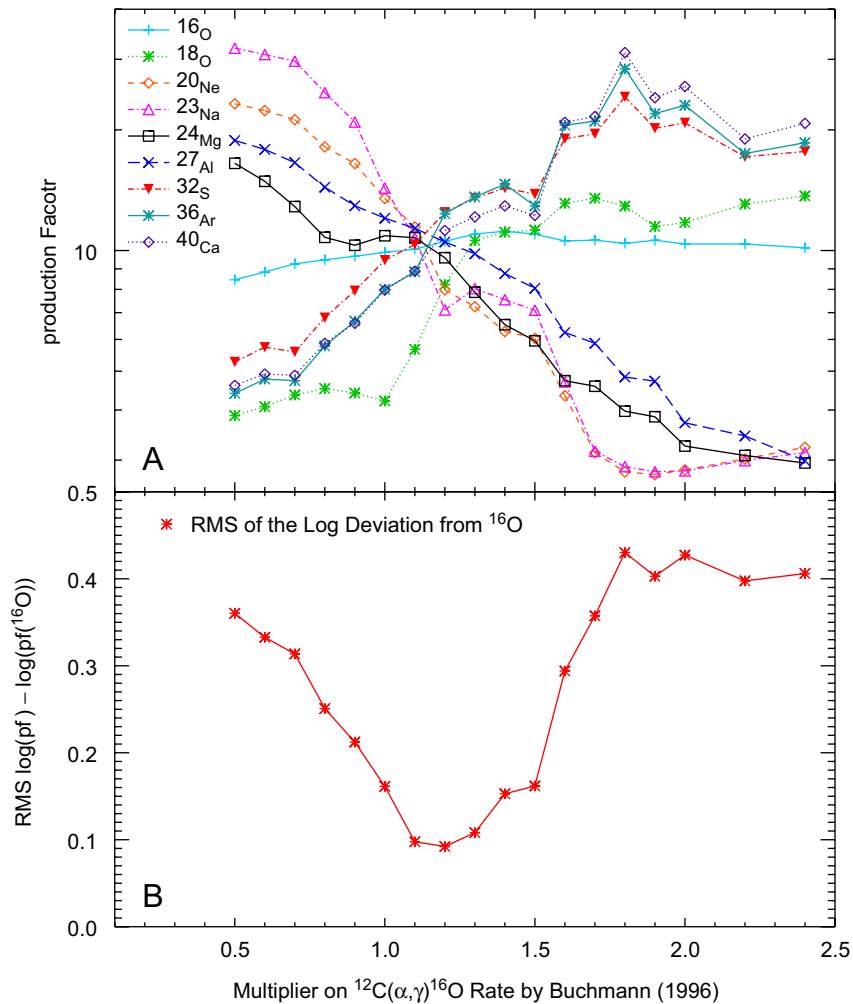


Fig. 1. Production factor of key elements for a set of solar metallicity stars folded with a Saltpeter birth function (Boyse et al., 2002).

1.2 times Buchmann (1996) was used in the present study. This is also consistent with recent measurements reported by Hammer et al. (2005) that give a best value of 1.08 times Buchmann-1996 (i.e., 162 ± 39 keV b). Of course, one could argue that the nucleosynthesis limit is also influenced by our uncertain model of stellar convection (Weaver and Woosley, 1993), in which case an experimental value ultimately near 170 keV b would serve to validate the treatment of convection in the code.

During the end of helium burning the $^{12}\text{C}(\alpha, \gamma)^{16}\text{O}$ rate competes with the triple-alpha reaction rate, and hence the uncertainty in that rate can have similar effects. In test calculations at 3×10^8 K and 1000 and 2000 g/cm³ we found that a 10% increase in the triple-alpha rate would have the same consequence as an 8% decrease in $^{12}\text{C}(\alpha, \gamma)^{16}\text{O}$. In a star, convection may change these results, though probably not much. The $^{12}\text{C}(\alpha, \gamma)^{16}\text{O}$ rate would need to be known better than about 10% before the uncertainty in the triple alpha rate, $\sim 12\%$ (Tur et al., 2007), became a limiting factor.

The other uncertain reaction rate that affects the abundances of hosts of nuclei, not just a few, is $^{22}\text{Ne}(\alpha, n)^{25}\text{Mg}$, which, along with $^{25}\text{Mg}(n, \gamma)^{26}\text{Mg}$, regulates the strength of the *s*-process in massive stars. The rate used here is the recommended value from Jaeger et al. (2001). The reaction $^{22}\text{Ne}(\alpha, \gamma)^{26}\text{Mg}$ competes with $^{22}\text{Ne}(\alpha, n)^{25}\text{Mg}$ for the destruction of ^{22}Ne and is thus also of some importance for determining the strength of the *s*-process. Here we use the lower bound for $^{22}\text{Ne}(\alpha, \gamma)^{26}\text{Mg}$ estimated by Käppeler et al. (1994). Other choices of strong and weak reaction rates have been discussed by Woosley et al. (2002). In particular, except where otherwise noted, we use the Hauser-Feshbach rates from Rauscher and Thielemann (2000) for reactions involving n, p, and α on heavy nuclei that lack experimental determination. This is of some relevance to the issue of ^{26}Al and ^{60}Fe production discussed later in the paper (Section 5.1).

2.2. Mass loss

Mass loss is known to be a powerful determinant in the evolution of stars of nearly solar metallicity, and its omission was one of the major shortcomings of the Woosley–Weaver 1995 survey (1995). For stars more massive than about $35 M_{\odot}$, mass loss is particularly important since it not only removes the hydrogen envelope, but shrinks the helium core appreciably. With current estimates of mass loss, a $100 M_{\odot}$ Population I star ends its life as a star of only about $6 M_{\odot}$, composed of helium and heavier elements only and no hydrogen left. This is similar to the mass and composition of the core of a $20 M_{\odot}$ star, and the explosion properties, remnant mass, and nucleosynthesis are radically different from a $100 M_{\odot}$ star that had no mass loss (see Section 3.1).

The mass loss prescription used here has also been discussed by Woosley et al. (2002). In particular, we use Nieuwenhuijzen and DeJager (1990) for mass loss on the main sequence and for red giants and Wellstein and Langer (1999) for Wolf–Rayet stars. The latter is based on the mass loss rate by Braun (1997) fit to observational data and divided by a factor of three to account for clumping Hamann and Koesterke (1998). The nucleosynthesis products carried away by stellar wind are included in all yields reported in this paper.

2.3. Convection and rotation

The treatment of convective physics, including overshoot mixing and semiconvection, follows the discussion in Woosley and Weaver (1988) and Woosley et al. (2002). In particular, we use a semi-convective mixing parameter, $\alpha = 0.1$, which results in relatively fast mixing in semiconvective regions. Mixing was treated in a time-dependent, mixing length formalism using the Ledoux criterion for instability. The fast semiconvection contributes significantly to mixing in regions that are stable to the Ledoux criterion but unstable to the Schwarzschild criterion, however, the mixing is less than that of a mere Schwarzschild mixing, taking into account the stabilizing effects of composition gradients.

Rotation can have a significant effect on both the presupernova evolution and the explosion mechanism. Here rotation was neglected, which is to say it is assumed that the change in helium core mass and dredge up of light isotopes due to rotationally induced mixing are small, for moderately fast rotating stars, and that the ratio of centrifugal force to gravity during the explosion is negligible. All these assumptions are questionable for rapidly rotating stars, especially so in small fraction of massive stars that become gamma-ray bursts (e.g., Woosley and Heger, 2006).

2.4. Initial abundances

The evolution and nucleosynthesis of a massive star both are sensitive to its initial composition. The total abundance of CNO affects the efficiency of hydrogen burning and the opacity. The conversion of CNO into ^{22}Ne during helium burning determines the “neutron excess”, which affects the production of all nuclei with unequal neutron and proton numbers. ^{22}Ne also provides the free neutrons necessary for the *s*-process during helium burning. Finally, because the yields of supernovae are traditionally normalized to ^{16}O , any change in the solar oxygen abundance affects the comparative ease with which all other heavy elements are produced.

It is thus a major occurrence in nucleosynthesis theory when the solar abundances, traditionally taken as representative of Population I stars in our Galaxy, are modified. Recent revisions to the solar abundance set have been discussed by [Lodders \(2003\)](#), [Asplund \(2005\)](#) and [Asplund et al. \(2005\)](#), . The abundances of all isotopes of CNO have been reduced by amounts of order 30% compared with the standard Anders and Grevesse values ([Anders and Grevesse, 1989](#)) of a few years ago. Here we use the [Lodders \(2003\)](#) set both as a starting composition, and also to normalize all computed yields.

2.5. Presupernova models

Using the KEPLER implicit hydrodynamics code ([Weaver et al., 1978](#)) and the physics specified above and in [Woosley et al. \(2002\)](#), stars of solar composition and various masses were evolved to the presupernova stage—defined by a collapse velocity in the core of 1000 km s^{-1} . Masses included in the study were 12–33 solar masses in steps of $1 M_{\odot}$, plus stars of 35, 40, 45, 50, 55, 60, 70, 80, 100, and $120 M_{\odot}$ —32 stars altogether. A future survey will use a much finer grid of masses, and the present work may be regarded as preliminary.

3. Simulating the explosion

As alluded to in the introduction, a robust description for how massive stars explode as supernovae remains elusive and this must surely affect our understanding of the origin of the elements. It is worth separating out that part of the nucleosynthesis that depends on the explosion mechanism from that which does not, however.

Certainly isotopes produced in the vicinity of what is commonly known as “the mass cut” are sensitive to conditions set up by the passage of the shock. This includes the yields of species made by explosive oxygen and silicon burning and in nuclear statistical equilibrium. More quantitatively, these are the species made at temperatures above $3 \times 10^9 \text{ K}$ and at radii less than about 7000 km, i.e., roughly the inner 1–2 solar masses of ejecta. Other species made by hydrogen, helium, carbon, neon and oxygen burning in hydrostatic equilibrium are not greatly affected (provided such material escapes the star and does not fall into a black hole), nor is the nucleosynthesis in the pre-explosive wind. On the other hand, the *r*-process and other species made in the neutrino-powered wind *are* quite sensitive to the explosion mechanism, and it is this sensitivity that makes them excellent diagnostics of the event.

As we shall see though, even the “explosive nucleosynthesis” below atomic mass 100 is not particularly sensitive to details of the explosion, provided that the star blows up with a “reasonable” kinetic energy and the explosion is not grossly asymmetric. This is basically because the shock conditions are determined by the pre-explosive structure and some simple physics, $4\pi R^3 a T^4 / 3 = \text{explosion energy} \approx 1 \text{ B}$.

Here, as elsewhere, the explosion is parameterized by a piston at constant Lagrangian mass coordinate that moves through the star with some specified radial history ([Woosley and Weaver, 1995](#); [Woosley et al., 2002](#)). The essential parameters of the piston are its location in mass and the final kinetic energy it imparts to the ejecta at infinity. Two different choices of each are explored: (a) piston mass at the edge of the iron core or at the point where the dimensionless entropy $S/N_A k = 4.0$; and (b) kinetic energies of 1.2 and 2.4 B. Thus for each mass, 4 explosion models were calculated for a total of 128 supernovae simulated.

The choices of piston mass and explosion energy are not free parameters, but are highly constrained by observations. The piston mass cannot be smaller than the iron core mass or unacceptable overproductions of $^{54,58}\text{Fe}$ and other neutron-rich species in the iron group will occur. On the other hand it cannot be much larger than the base of the oxygen shell ($S/N_A k = 4$) or, as we shall see, typical neutron star masses will be too large. The large density decrease associated with the base of the oxygen shell is also dynamically important and successful explosion calculations, when they occur, frequently find the mass cut there ([Fig. 2](#)). The explosion energy is constrained to be 1–2 B by observations

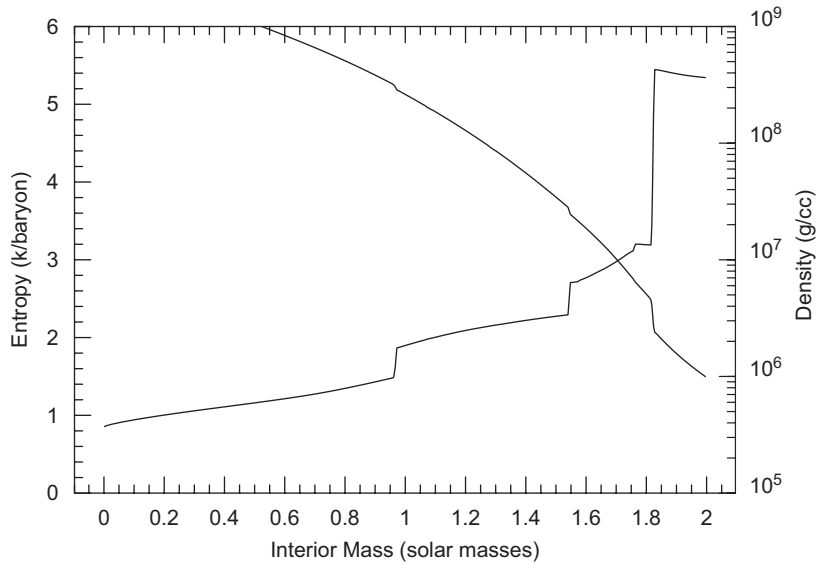


Fig. 2. Entropy and density distributions inside a 20 solar mass presupernova star. The iron core mass here is $1.54 M_{\odot}$; the base of the oxygen shell is at $1.82 M_{\odot}$. The sudden decrease in density at the base of the oxygen shell causes an abrupt decline in ram pressure which often results in explosions happening with this mass cut.

of SN 1987A (Bethe, 1990; Arnett et al., 1989) which was a Type II supernova of typical mass (about $18\text{--}20 M_{\odot}$). It is also constrained by the observed light curves of Type II supernovae (Section 3.2).

3.1. Remnant masses

Observations by Thorsett and Chakrabarty (1999) of a large number of pulsars in binary systems give a narrow spread in masses, $1.35 \pm 0.04 M_{\odot}$. There must be room for some diversity, however. Ransom et al. (2005) present compelling evidence for a pulsar in the Terzian 5 globular cluster with a gravitational mass of $1.68 M_{\odot}$. The remnant gravitational masses for our survey using the Kepler stellar evolution code, with $KE = 1.2 B$ and pistons located the edge of the iron core, are plotted in Fig. 3. A more careful analysis of fall back in these models using an Eulerian hydrodynamics code and a better treatment of the inner boundary conditions has been carried out by Zhang et al. (2007), but gives similar numbers for solar metallicity stars. Using the Zhang et al. (2007) values, adopting a Salpeter initial mass function with $\Gamma = 1.35$ to describe the birth frequency of these stars, and assuming a maximum neutron star mass of $2.0 M_{\odot}$, one obtains an average *gravitational mass* for the neutron star of 1.47 ± 0.21 if the piston is at the $S/N_A k = 4.0$ point and 1.40 ± 0.22 if it is at the edge of the iron core. If the maximum neutron star mass is $1.7 M_{\odot}$, the numbers are changed to $1.41 \pm 0.15 M_{\odot}$ and 1.34 ± 0.14 , respectively. In this paper, we carried out simulations with the piston at both points—the iron core edge, and the base of the oxygen shell. Larger masses than typical are also possible for the rare exceptionally massive star, usually those over $25 M_{\odot}$. For those cases where a black hole was made, its average mass was around $3 M_{\odot}$. We note that these numbers are for single stars and they could be altered significantly in mass exchanging binaries.

The figure also shows that neutron stars are made by both the lightest main sequence stars and the heaviest. This is a consequence of mass loss. The helium core mass of the presupernova star increases monotonically with main sequence mass up to about $45 M_{\odot}$, where it reaches a maximum of $13 M_{\odot}$. Beyond that the helium core shrinks due to efficient Wolf–Rayet mass loss and the iron core mass shrinks with it. A $100 M_{\odot}$ model had a total mass of only $6.04 M_{\odot}$ when it died—all helium and heavy elements—and an iron core mass of $1.54 M_{\odot}$.

The results are quite different for stars with low metallicity and, hence, reduced mass loss (Heger and Woosley, 2007; Zhang et al., 2007). Fig. 4 shows that the remnant mass increases rapidly for main sequence masses above about $35 M_{\odot}$ and continues to increase at higher masses. These large masses are due to fall back. A $1.2 B$ explosion is inadequate to unbind the entire star, especially given the large helium core (Woosley et al., 2002) and effect of the reverse

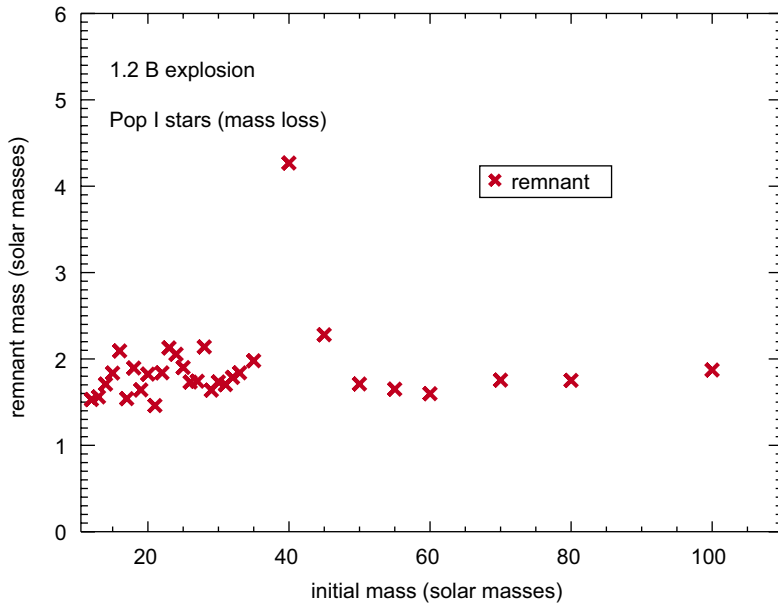


Fig. 3. Fe core masses for a grid of stellar masses. Solar metallicity stars. See text for explanation.

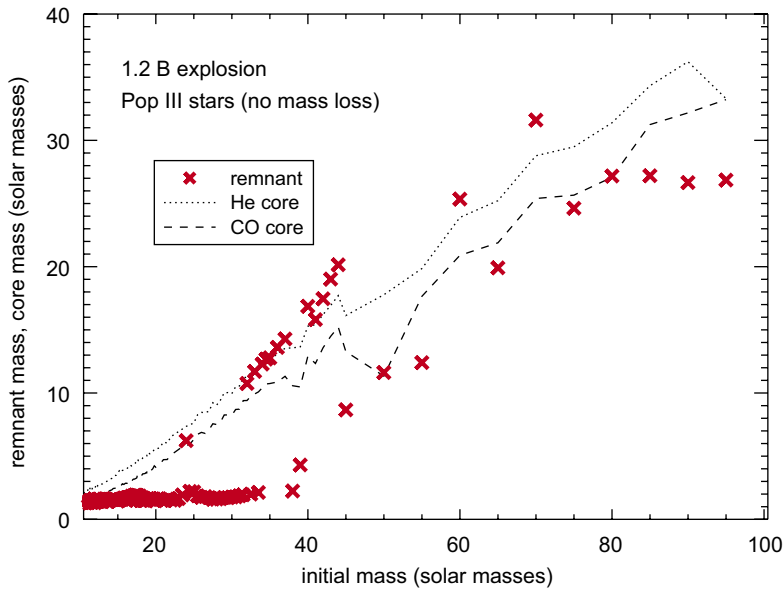


Fig. 4. Fe core masses for a grid of stellar masses. Zero metallicity stars. Many more black holes are made because the star loses little mass during its evolution to presupernova. The two branches of black hole masses at high main sequence mass correspond to red (lower branch) and blue (upper branch) supergiant progenitors. The lower carbon-oxygen core masses for the red supergiant cases reflect dredge up and primary nitrogen production (Zhang et al., 2007; Heger and Woosley, 2007).

shock. A $100 M_{\odot}$ main sequence star now dies with a helium core of $42 M_{\odot}$, well into the pulsational pair instability domain (Heger and Woosley, 2002). Unless supernova engines of much greater power than 1.2 B become available at low metallicity, these stars will make black holes, not neutron stars, and if the rotation rate is sufficient, gamma-ray bursts.

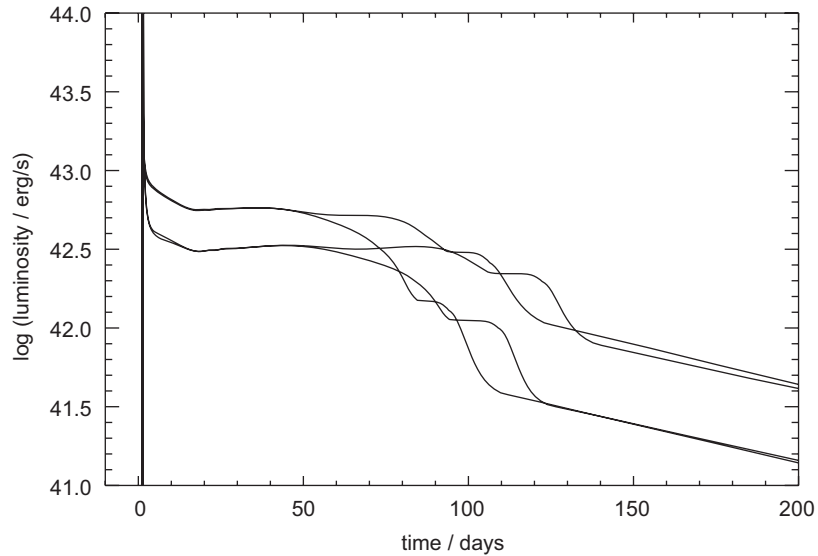


Fig. 5. Light curve of a 15 solar mass supernova. The four curves represent two choices of explosion energy and combined with two choices of mass cut. The presupernova star was a red supergiant.

One may also note the existence of two branches of black hole remnants above $35 M_{\odot}$ in Fig. 4. Zhang et al. (2007) find that these branches correspond to two different classes of progenitors—red supergiants, which experience a lot less fallback during the reverse shock (Chevalier, 1989)—and more compact, extremely blue supergiants. If the star produces primary nitrogen due to the interpenetration of the helium convective core and hydrogen envelope, it swells to red giant proportions, has a weaker reverse shock, and leaves a smaller remnant mass.

3.2. Light curves

The KEPLER code includes radiative diffusion and can thus be used to calculate approximate light curves for the supernovae it produces. The code is limited by using a single temperature for the radiation and the matter, and assumes blackbody radiation, but these are not bad approximations during the plateau stage of Type II supernovae (Weaver and Woosley, 1980; Eastman et al., 1994). The principal opacity source is electron scattering with the free electron abundance determined by solving the Saha abundances of all ions for the 19 isotopes in the reaction network (Ensmann and Woosley, 1988). A floor opacity of $10^{-5} \text{ cm}^2 \text{ g}^{-1}$ is used in regions that have recombined. The abundance of ^{56}Ni is taken from the nucleosynthesis calculation and moderate mixing of the helium core is assumed.

The resulting light curves for four explosions of a $15 M_{\odot}$ supernova are given in Fig. 5 for cases where the mass cut was taken at the edge of the iron core and at the location where the entropy equals $4 k_{\text{B}}$ /baryon. Two explosion energies, 1.2 and 2.4 B were employed. The explosions that had the higher kinetic energy were brighter on the plateau and the ones with the deeper mass cut (and hence more ^{56}Ni ejected) had the brighter tails. The mass of ^{56}Ni ejected was $0.086 M_{\odot}$ for the 1.2 B explosion with the mass cut at $S = 4 k_{\text{B}}$ /baryon; $0.096 M_{\odot}$ for the 2.4 B explosion with mass cut at $S = 4 k_{\text{B}}$ /baryon; $0.27 M_{\odot}$ for the 1.2 B explosion with the mass cut at the edge of the iron core; and $0.31 M_{\odot}$ for the 2.4 B explosion with the mass cut at the edge of the iron core.

Clearly, the models with higher kinetic energy are brighter on the plateau (see also Popov, 1993). In fact, if the kinetic energy were any larger than 2.4 B, the supernova would be far brighter than average Type IIp supernovae. On the other hand if the explosion energy were much less than 1 B, large amounts of material would fall back, increasing the masses of the neutron star remnants beyond acceptable values and robbing the nucleosynthesis of its most prolific sources. We conclude that the range 1.2–2.4 B is the relevant one for modern supernovae in solar metallicity stars and these are the values employed in the nucleosynthesis survey.

4. Nucleosynthetic yields

The integrated yields of the elements are given for four different choices of mass cut and explosion energy in Fig. 6. Whether one places the piston at the edge of the iron core or the base of the oxygen shell and whether the explosion energy is 1.2 or 2.4 B makes little difference except to the iron group. There the difference is of order a factor of two, with lower iron yields obviously resulting from lower explosion energies and shallower pistons. In all cases the iron group synthesis is low compared both with C, O, Ne, and Na and with *s*-process production above Ni. One expects from one-half to two-thirds of the iron group to come from Type Ia supernovae (Timmes et al., 1995) which are not included here. The *s*-process, which is secondary in nature, will be underproduced in stars of less than solar metallicity, so a factor of two extra here relative to oxygen is not undesirable.

Fig. 7 shows the integrated nucleosynthesis (the yields folded with a Salpeter initial mass function with $\Gamma = -1.35$) for all elements up to lead compared with the isotopic composition of the sun. Fig. 8 shows the corresponding comparison of isotopes. Overall, the agreement is quite good, especially considering that several known sites of important

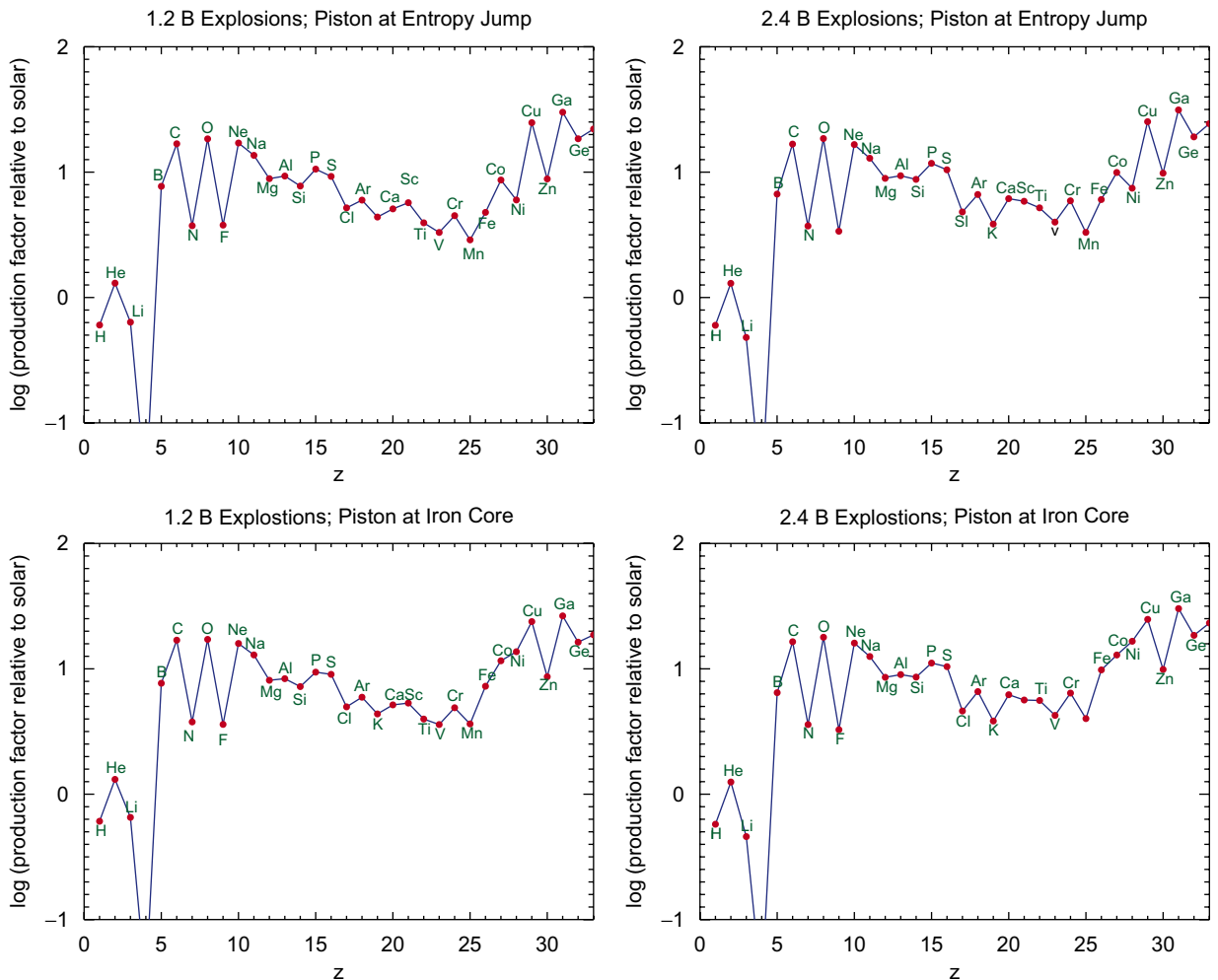


Fig. 6. Elemental yields integrated over a Salpeter initial mass function for solar metallicity stars with masses from $12 M_{\odot}$ to $120 M_{\odot}$. Calculations were carried out for two choices of explosion energy (1.2, 2.4 B) and two piston location (at the place where the entropy jumps to $S/N_A k = 4$ and at the edge of the iron core). Only minor differences are discernible. Similarly small changes occur when the slope of the IMF is changed from -1.35 (Salpeter) to a gentler -0.9 .

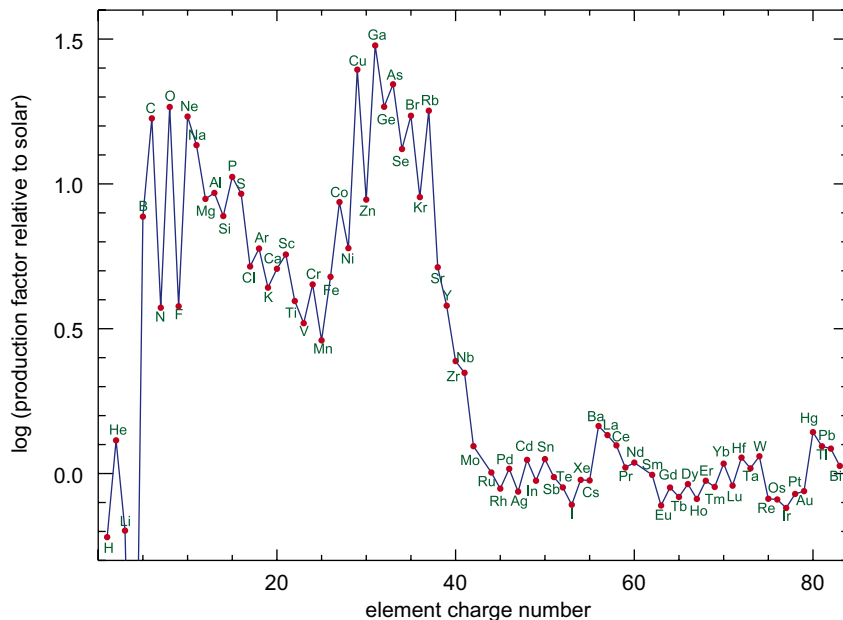


Fig. 7. Elemental yields when the grid of supernova masses is integrated over a Salpeter initial mass function. The explosion energy was 1.2 B and the piston was located at the mass coordinate where $S/N_A k = 4.0$. A strong s -process operates up to $Z = 40$.

nucleosynthesis have been omitted. Classical novae will need to produce ^{15}N and ^{17}O , though some ^{15}N is made here by the neutrino spallation of ^{16}O . The isotopes ^{44}Ca , ^{47}Ti , and ^{48}Ca are underproduced and may come from some rare form of SN Ia (Woosley, 1997) or asymmetric supernova. The overabundance of ^{40}K is not a concern since some will decay before the sun is born. Also missing are ordinary Type Ia supernovae, which contribute half or more of the iron group, and asymptotic giant branch stars which make ^{14}N and the s -process. In fact, the full production of carbon here is a novel and surprising result, since it is usually attributed to low mass stars. It is made here chiefly in the winds of very massive Wolf–Rayet stars and its production is facilitated by the new lower solar abundance (Lodders, 2003).

Finally, conspicuously absent is the r -process and other products of the neutrino-powered wind. The wind of a young neutron star is a prolific source of heavy elements, accounting for about half of the isotopes in nature. These include not only the r -process (Woosley et al., 1994), but some important p -process nuclei (Pruet et al., 2006; Fröhlich et al., 2006), and even abundant elements like Zn (Hoffman et al., 1996) and Sc (Pruet et al., 2005). Hans Bethe was very interested in the neutrino-powered wind and the r -process, and he was working on it when SEW last saw him in Winter 2003. This was probably his last supernova-related project. He said that he had an abiding interest in uranium.

5. The special cases of ^{26}Al and ^{60}Fe

Having computed the isotopic nucleosynthesis in a grid of stars up to $120 M_{\odot}$, including the contribution of the winds the more massive stars make as Wolf–Rayet stars, we turn to the examination of two isotopes of special interest to gamma-ray line astronomy. The long-lived isotopes ^{26}Al and ^{60}Fe accumulate in the interstellar medium from thousands of supernovae and thus serve as calibrations on the integrated yields of massive stars. Observations by RHESSI (Smith, 2004) and INTEGRAL (Harris et al., 2005) give a ratio of fluxes from the decays of ^{26}Al and ^{60}Fe of 0.16 and 0.11 ± 0.03 , respectively. Both measurements are quite consistent with the predicted value, 0.16 , by Timmes et al. (1995) based upon yields from the Woosley and Weaver (1995) survey. Later calculations (Rauscher et al., 2002; Limongi and Chieffi, 2003), however, using stellar and nuclear physics that was nominally “improved” gave a much larger synthesis of ^{60}Fe that was not in line with observations (Prantzos, 2004).

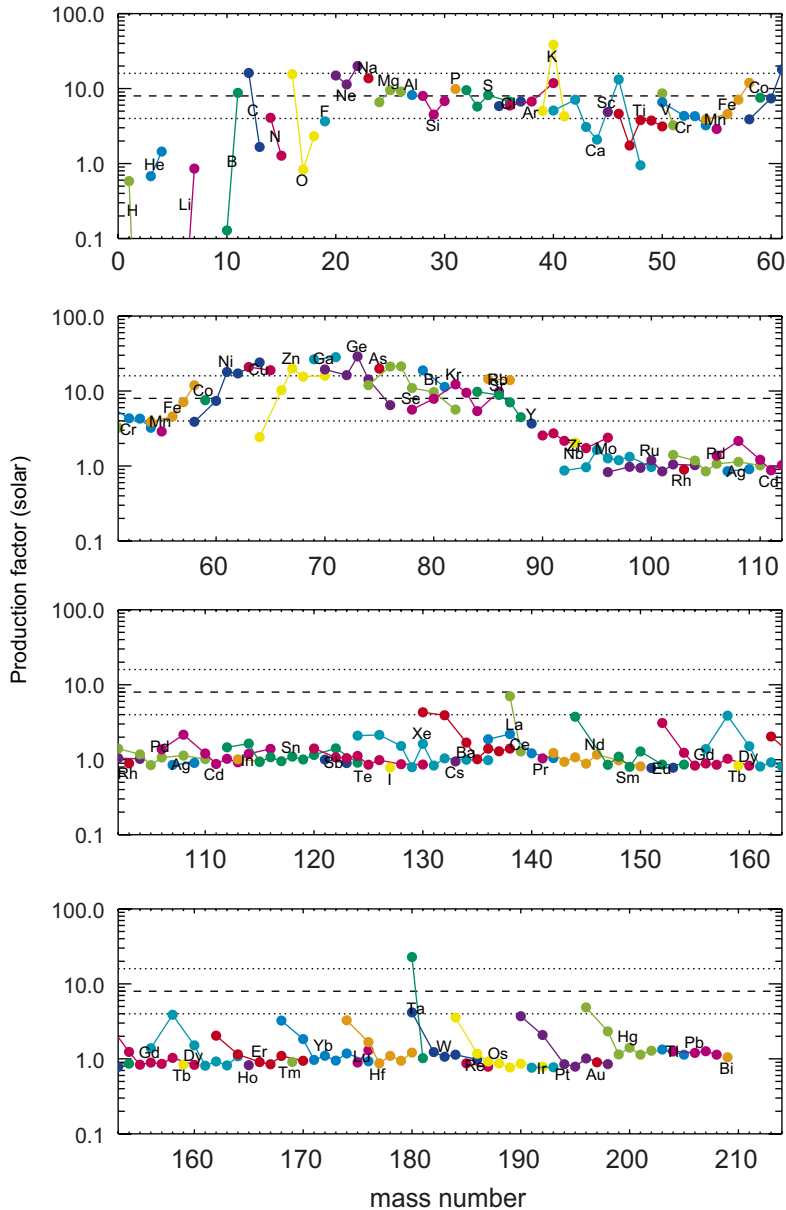


Fig. 8. Isotopic nucleosynthesis integrated over a Salpeter initial mass function. The results are in good agreement with solar abundances below $A = 85$. The excess of s -process nuclei above the iron group is needed in part, to compensate for the smaller production of these secondary nuclei in stars of slightly lower metallicity. The γ -process is mostly successful in making the neutron-deficient isotopes (the “ p -nuclei”) above $A = 130$, but there is an annoying deficiency of p -nuclei production from $A = 90$ to 130 . The large productions of ^{11}B , ^{19}F , ^{138}La , and ^{180}Ta , are due to the neutrino process. Products of the neutrino wind, e.g., ^{64}Zn and the r -process, are not included in this plot.

The ratio of gamma-line fluxes implies, in steady state, a synthesis ratio by mass of $^{60}\text{Fe}/^{26}\text{Al}$ of 60/26 times the flux ratio, or about 0.3. (The steady state abundance is inversely proportional to the decay rate and the flux is the abundance times the decay rate so the decay rate itself cancels.) Timmes et al. (1995) gave a theoretical ratio of 0.38 with an expected uncertainty of a factor of 1.7. Using the larger grid of models here, however, and including mass loss as discussed in Section 2.2, we calculate a ratio of 1.8, i.e., six times too large. This large excess of $^{60}\text{Fe}/^{26}\text{Al}$ is consistent with what Rauscher et al. (2002) found, even though their calculations did not include the quite massive stars studied here (up to $120 M_{\odot}$), nor their mass loss. What is wrong?

5.1. Nuclear physics uncertainties

One problem is certainly the use of uncertain nuclear reaction rates in all studies to date. In making the transition to the reaction rate data base of [Rauscher and Thielemann \(2000\)](#), we erroneously used the new Hauser Feshbach rates especially for $^{26}\text{Al}(n,p)^{26}\text{Mg}$ and $^{26}\text{Al}(n,\alpha)^{23}\text{Na}$. These are the principal means of ^{26}Al destruction in the carbon and neon layers where ^{26}Al is explosively synthesized. The Rauscher–Thielemann rate for $^{26}\text{Al}(n,p)^{26}\text{Al}$ at 2×10^9 K, for example, is $1.4 \times 10^8 \text{ cm}^3 \text{ Mol}^{-1} \text{ s}^{-1}$. The Rauscher–Thielemann rate for $^{26}\text{Al}(n,\alpha)^{23}\text{Na}$ at 2×10^9 K is $2.6 \times 10^7 \text{ cm}^3 \text{ Mol}^{-1} \text{ s}^{-1}$. These are both a factor of 3 to 5 higher than the rates used for these reactions by [Woosley and Weaver \(1995\)](#) and the *experimental* determinations by [Koehler et al. \(1997\)](#) and [Caughlan and Fowler \(1988\)](#).

A second effect, less important than the cross sections, is a super-hot helium shell (4×10^8 K) in several of the pre-supernova star. This shell's existence was traced to the use of OPAL opacities in a region where they may not be appropriate, a region where electron scattering dominates. Using the electron scattering opacity of [Weaver et al. \(1978\)](#) just in high temperature regions where electron scattering dominates decreased the ^{60}Fe yield significantly, but this was only in a few stars.

Using what we believe to be more nearly correct cross sections for ^{26}Al destruction (though still uncertain) and adjusting the opacity as described, the integrated yield of ^{60}Fe to ^{26}Al is reduced to 0.95. This is for a standard Salpeter IMF with $\Gamma = -1.35$. If we instead change the slope to -0.90 , i.e., enhance the production of very massive stars, the ratio is reduced slightly to 0.81. Even then one-half the yield of ^{26}Al comes from stars under $35 M_{\odot}$, not the more massive ones and their Wolf–Rayet winds.

There are further uncertainties to explore, however. Several of the cross sections governing the production of ^{60}Fe are also highly uncertain. The reaction $^{59}\text{Fe}(n,\gamma)^{60}\text{Fe}$ affects its synthesis and $^{60}\text{Fe}(n,\gamma)^{61}\text{Fe}$ controls its destruction. Neither is measured, though both could be, admittedly with difficulty. Interestingly, both changed in the [Rauscher and Thielemann \(2000\)](#) tabulation in such a direction as to increase ^{60}Fe production. The tabulation by [Woosley et al. \(1978\)](#) had, for helium burning temperatures, a rate for $^{59}\text{Fe}(n,\gamma)^{60}\text{Fe}$ half as large and a rate for $^{60}\text{Fe}(n,\gamma)^{61}\text{Fe}$ twice as large. When the older rates were used for a select set of models, the ^{60}Fe production was reduced by about a factor of two.

The final *nuclear* uncertainty is the rate governing the production of neutrons where ^{60}Fe is made, i.e., $^{22}\text{Ne}(\alpha,n)^{25}\text{Mg}$. The rate included in our network ([Jaeger et al., 2001](#)) is increased from what was used in 1995. If we reduce its value in a few select models by a factor of two (within the error bar), ^{60}Fe production is again decreased by up to a factor of two, though usually the effect was smaller.

All things considered, variation of only the nuclear physics, bringing uncertain cross sections back to the values they had in the Timmes et al. survey, could account for most of the difference in the present calculations and the observations. *Hence further progress in this important field of astronomy depends upon more accurate measurements and estimates of critical nuclear physics.*

5.2. Uncertainties in the stellar models

This is not to say that non-nuclear effects are unimportant. Metallicity, mass loss, rotation, and an uncertain IMF certainly all play major roles. [Palacios et al. \(2005\)](#) have explored ^{26}Al production in models of massive stars that include rotationally induced mixing, as well as mass loss and different choices of metallicity. An explicit comparison with a couple of our models is educational. For a $60 M_{\odot}$ main sequence star with $Z = 0.02$ and no rotation, they find an ^{26}Al production in the pre-explosive wind of the star of 1.30×10^{-4} and a final star mass of $12.4 M_{\odot}$ ([Meynet and Maeder, 2000](#)). For our $60 M_{\odot}$ model with metallicity $Z = 0.016$ and using the smaller experimental rates for $^{26}\text{Al}(n,p)^{26}\text{Mg}$ and $^{26}\text{Al}(n,\alpha)^{23}\text{Na}$, we find a production in the wind of $1.1 \times 10^{-4} M_{\odot}$ and a final mass of $8.0 M_{\odot}$. But we also find an additional $9.9 \times 10^{-5} M_{\odot}$ of ^{26}Al is produced in the explosion of the remaining star, chiefly by explosive neon burning. This is good agreement, and shows that the explosion and wind may contribute comparable amounts to ^{26}Al synthesis even for a $60 M_{\odot}$ progenitor. [Palacios et al. \(2005\)](#) further explore the dependence of metallicity and rotation though, and find ^{26}Al production in the wind of this same star is increased to $2.2 \times 10^{-4} M_{\odot}$ if the rotation rate is 300 km s^{-1} on the main sequence, or $3.0 \times 10^{-4} M_{\odot}$ with no rotation but $Z = 0.04$. Combining both effects, $Z = 0.04$ and $v_{\text{rot}} = 300 \text{ km s}^{-1}$, the ^{26}Al production in the wind becomes even larger $7.2 \times 10^{-4} M_{\odot}$. While one must be concerned that increasing the metallicity may also increase the ^{60}Fe yield and thus not increase the $^{60}\text{Fe}/^{26}\text{Al}$ ratio ([Prantzos, 2004](#)), this does show the sensitivity of ^{26}Al to reasonable variations in rotation rate. For a $120 M_{\odot}$ model,

the effect is even greater is similar. For $Z=0$, $v_{\text{rot}}=0$, Palacios et al. (2005) obtain an ^{26}Al mass of $5.7 \times 10^{-4} M_{\odot}$ in the wind while we have $4.9 \times 10^{-4} M_{\odot}$ plus $2.9 \times 10^{-5} M_{\odot}$ made in the explosion. With $Z=0.04$ and $V_{\text{rot}}=300 \text{ km s}^{-1}$, Palacios et al. (2005) get a whopping $2.2 \times 10^{-3} M_{\odot}$.

Limongi and Chieffi (2006) have also recently (after our present study was completed) examined the sensitivity of ^{60}Fe and ^{26}Al production to the prescription for mass loss and the slope of the IMF. They find that both can make an appreciable difference.

6. Conclusions

We still do not understand exactly how massive stars explode, far less the variation of explosion properties—especially mass cut and explosive kinetic energy—with main sequence mass. This remains a forefront problem in nuclear astrophysics research to which Hans Bethe contributed greatly. It is likely, in the final analysis, that the physical intuition, terminology, and convective, neutrino-powered paradigm that he and his colleagues brought to the field will form the basis of a complete understanding, though we aren't there yet (Woosley and Janka, 2005). Certainly, the low entropy, super-nuclear density bounce following the initial collapse will be phase one of any massive star explosion.

This lack of a first principles understanding of the explosion mechanism, however, is not a fundamental roadblock on our path to understanding the origin of (almost all of) the elements. Arguments have been presented here to show that the mass cut is highly constrained by nucleosynthesis and observed neutron star masses. The explosion energy in common Type II supernovae is also mostly in the range 1.2 B plus or minus a factor of two. Exploding a large range of stellar masses with pistons located either at the edge of the iron core or the base of the oxygen burning shell—the maximum range allowed—and with explosion energies of either 1.2 or 2.4 B gives very similar nucleosynthesis. The iron group is most affected and the magnitude of the uncertainty is about a factor of two.

The nucleosynthesis that results (Figs. 7 and 8) agrees reasonably well with solar abundances. There are some changes caused by the recent downward revisions of the solar CNO abundances, and at first glance the agreement is worsened by these changes. Since ^{16}O is our standard normalization point in nucleosynthesis studies, since we now need to make less of it, the production of all other heavier elements is decreased. Yields that previously would have coproduced Si and O say, in solar proportions, now overproduce O (Fig. 8). The production of odd- Z elements and odd- A isotopes is also decreased because the initial CNO in the star later becomes the ^{22}Ne that sets the neutron excess for carbon, neon, and oxygen burning (Section 2.4). Still the agreement is not too bad, and most of the missing species ^{13}C , $^{14,15}\text{N}$, ^{48}Ca , etc. can be attributed to other sites than massive stars.

The outstanding problem in nucleosynthesis theory presently is a full understanding of the r - and p -processes. The latter has an appreciable contribution from explosive neon and oxygen burning (shown in Fig. 8) for A greater than 130, but is underproduced for lighter masses. The solution for both the r -process and the light p -process probably lies in the neutrino-powered wind. Current models give inadequate entropy in the wind and this may be where nucleosynthesis can be an important diagnostic of the explosion model (e.g., Burrows et al., 2006).

The nucleosynthesis of the long-lived radioactivities ^{26}Al and ^{60}Fe is an important constraint on the stellar models, and one that is largely independent of the explosion mechanism. The abundances inferred from gamma-ray line astronomy may have important implications for rotationally induced mixing, convection theory, mass loss theory, the initial mass function for massive stars, and the distribution of metals in the galaxy. The synthesis is also quite sensitive to nuclear reaction rates whose uncertain values could be better determined in the laboratory, however. In particular, the discrepancy between observations of the $^{60}\text{Fe}/^{26}\text{Al}$ ratio and recent calculations—this work and Rauscher et al. (2002)—may involve a “perfect nuclear storm” of erroneous choices. The rates affecting ^{26}Al destruction were almost certainly too high; the rates affecting ^{60}Fe production, namely $^{59}\text{Fe}(n, \gamma)^{60}\text{Fe}$ and $^{22}\text{Ne}(\alpha, n)^{25}\text{Mg}$, may have been too high; and the rate for its destruction, $^{60}\text{Fe}(n, \gamma)^{61}\text{Fe}$ may have been too low. Given the choices made by Woosley and Weaver (1995), the prediction of Timmes et al. (1995), which agrees with observations, is still defensible. In any case, important inferences about the stellar models will only be credible (and necessary), when these uncertain rates have been better determined.

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