NUCLEOSYNTHETIC CONSTRAINTS ON THE MASS OF THE HEAVIEST SUPERNOVAE

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Received 2013 February 5; accepted 2013 April 9; published 2013 May 9

ABSTRACT

We explore the sensitivity of nucleosynthesis in massive stars to the truncation of supernova explosions above a certain mass. It is assumed that stars of all masses contribute to nucleosynthesis by their pre-explosive winds, but above a certain limiting main sequence mass, $M_{\text{BH}}$, the presupernova star becomes a black hole and ejects nothing more. The solar abundances from oxygen to atomic mass 90 are fit quite well assuming no cutoff at all, i.e., by assuming all stars up to 120 $M_{\odot}$ make successful supernovae. Little degradation in the fit occurs if $M_{\text{BH}}$ is reduced to 25 $M_{\odot}$. If this limit is reduced further however, the nucleosynthesis of the $s$-process declines precipitously and the production of species made in the winds, e.g., carbon, becomes unacceptably large compared with elements made in the explosion, e.g., silicon and oxygen. By varying uncertain physics, especially the mass loss rate for massive stars and the rate for the $^{22}\text{Ne}(\alpha, n)^{25}\text{Mg}$ reaction rate, acceptable nucleosynthesis might still be achieved with a cutoff as low as 18 $M_{\odot}$. This would require, however, a supernova frequency three times greater than the fiducial value obtained when all stars explode in order to produce the required $^{16}\text{O}$. The effects of varying $M_{\text{BH}}$ on the nucleosynthesis of $^{56}\text{Fe}$ and $^{26}\text{Al}$, the production of helium as measured by $\Delta Y/\Delta Z$, and the average masses of compact remnants are also examined.

Key words: galaxies: abundances – hydrodynamics – nuclear reactions, nucleosynthesis, abundances – stars: abundances – supernovae: general

Online-only material: color figures, machine-readable table

1. INTRODUCTION

Just which massive stars explode as supernovae and which collapse to black holes has been a topic of great interest for a long time. In particular, stellar nucleosynthesis can be used to constrain the maximum mass of the supernova that needs to (or can) explode in order to explain the abundances of the elements seen in the Sun and elsewhere (e.g., Twarog & Wheeler 1982, 1987; Maeder 1992). Previous works have generally focused on the production of helium and oxygen and the ratio $\Delta Y/\Delta Z$, where $Y$ is the helium mass fraction and $Z$ is the heavy element fraction. Maeder (1992), for example, concludes that the observed abundances are best fit if stars of all masses contribute their pre-explosive winds, but only stars below 20–25 $M_{\odot}$ explode as supernovae (though see Prantzos 1994 who contested this conclusion). The remainder presumably end up as black holes which accrete the remaining star, including all its heavy elements.

Added interest in this issue has been generated recently by the increasingly tight observational constraints placed upon the masses of presupernova stars. Smartt (2009) finds no evidence for supernova progenitors with masses over 20 $M_{\odot}$. Horiuchi et al. (2011) also find an inconsistency with the measured rate of core collapse supernovae and the cosmic star formation rate in the sense that more stars seem to form than are observed to die as supernovae by a factor of about two. Of course, these arguments are not yet absolute. More massive supernovae may be hidden in dust, and the connection between main sequence mass and presupernova mass relies on theory. Star formation rates and supernova rates are not precisely known, but these constraints may become tighter with time and certainly suggest that not all massive stars make luminous supernovae.

On the theoretical front, it has been known for a long time that more massive stars are harder to blow up than lower mass ones (e.g., Fryer 1999; Fryer & Heger 2000). With higher mass, the entropies around the collapsing iron cores are greater, and the fall off of density with radius is consequently more gradual. During the collapse, this means a greater accretion rate on the proto-neutron star that is harder to reverse. O’Connor & Ott (2011) recently quantified this effect with a “compactness parameter” (see their Figure 9) and measured the difficulty of blowing up stars in a 1D code as a function of that parameter. Interestingly, they also concluded that stars heavier than 20 $M_{\odot}$ were harder to explode.

These considerations motivate revisiting the problem of stellar nucleosynthesis as a function of mass. Using a fiducial set of solar metallicity models from Woosley & Heger (2007), the same model set used by O’Connor & Ott (2011), we study the nucleosynthesis and remnant masses resulting if the supernova explosions are truncated above a certain mass, $M_{\text{BH}}$. A Salpeter initial mass function is assumed (Salpeter 1955) with a slope of $\Gamma = -1.35$. We determine not only the bulk nucleosynthetic properties like oxygen and remnant mass as a function of $M_{\text{BH}}$, but also examine the synthesis of the $s$-process, the individual ratios of important intermediate mass and light elements, and the synthesis of interstellar radioactivities, $^{26}\text{Al}$ and $^{60}\text{Fe}$.

2. MODELS

The yield tables of Woosley & Heger (2007) give the nucleosynthesis of all species from hydrogen through lead for supernovae resulting from non-rotating massive stars with solar metallicity for the following initial masses: 12–33 (every integer mass), 35–60 (every 5 masses), 60–80 (every 10 masses), 100, and 120 solar masses. The authors calculated explosions for four sets of models parameterized by the mass cut and explosion energy. Here we use their standard set for which the explosion energy was $1.2 \times 10^{51}$ erg and the mass cut was located at the “entropy jump” where $S/N_{\text{Ak}} = 4.0$. These are their “A” models and are the same models for which Zhang
et al. (2008) calculated compact remnant masses and O’Connor & Ott (2011) studied compactness. The spread of these models can be seen in Figure 1. Nucleosynthesis ejected by the pre-explosive winds and in the explosions was archived separately, can be seen in Figure 1. Nucleosynthesis ejected by the pre-

mass function described by Reid & Wilson (2006) as illustrated

some key species are provided in the online supplement for this

The binning indicates the binning used in our grid of stellar models.

The Salpeter initial mass function is a model that represents the

Equation (2), where

\[ \int_{M_{\odot}}^{M_{\text{BH}}} \Phi(M) dM \propto M^{-2.35_{-0.1}^{+0.2}}. \]  

The total yields of the stellar population were calculated by integrating the yields over the mass function, as described in Equation (2), where \( m_i \) is the total production (in solar masses) of isotope \( i \), and \( E_i(M) \) and \( W_i(M) \) are the total ejecta of isotope \( i \) from, respectively, the supernova explosion and the winds in

\[ m_i = \int_{12M_{\odot}}^{M_{\text{BH}}} \Phi(M) E_i(M) dM + \int_{12M_{\odot}}^{120M_{\odot}} \Phi(M) W_i(M) dM. \]  

Notes. A subset of the yields from the ‘A’ series of models from Woosley & Heger (2007), where \( M \) is the mass of the star in solar masses. The supernova yields for each element are also presented in solar masses. A much more extensive table, including yields for Si, S, Ar, Ca, 70Ge, 76Se, 86Sr, 87Sr, 89Al, and 90Fe up to 120 \( M_{\odot} \) is provided as an electronic addition to this publication. In addition to the supernova yields, the electronic table also separately includes the presupernova mass loss yields for each of these elements in each model.

(This table is available in its entirety in a machine-readable form in the online journal. A portion is shown here for guidance regarding its form and content.)

Notes. \( M_{\text{BH}} \) is the heaviest supernova mass, \( ^{16}\text{O} \) is the production factor of the isotope, Mean (16–59) and \( \sigma \) (16–59) are the arithmetic mean and standard deviation of the production factors for isotopes with atomic mass between 16 and 59, Mean (60–84) and \( \sigma \) (60–84) are the corresponding values for isotopes with atomic mass between 60 and 84, and \( N_{SN} \) is the relative number of supernovae needed to produce the same amount of \( ^{16}\text{O} \).
Figure 2. The production factor (plotted logarithmically) as a function of atomic mass when no truncation of supernovae is assumed, i.e., when stars as heavy as 120 \( M_\odot \) continue to explode. The dashed line represents the production factor of \( ^{16}\text{O} \). The shorter dashed lines represent a factor of two deviation from \( ^{16}\text{O} \).

(A color version of this figure is available in the online journal.)

Our results are expressed in terms of a simple “production factor” for each isotope defined as

\[
P_i = \frac{m_i}{\sum S_i},
\]

where \( S_i \) is the mass fraction of the isotope in the Sun (Lodders 2003). The importance of the production factor lies in its relationship to the supernova rate. It can be shown that the production factor from high-mass progenitors is inversely proportional to the number of supernovae estimated by the model, assuming that the majority of the isotope’s production comes from this stellar population.

For comparison, we plot the production factors as a function of atomic mass for a population with no upper bound in Figure 2 (see also Woosley & Heger 2007).

3. LIMITS ON \( M_{BH} \)

The mass of the heaviest supernova that has to explode is constrained by a variety of observations. These include not only the nucleosynthetic pattern of the intermediate mass elements, but the light component of the \( s \)-process, the frequency of supernovae, and the masses of compact remnants. The existence of a cutoff mass also has interesting implications for supernovae, and the masses of compact remnants. The existence of stellar populations with different upper mass limits for supernovae is also of interest.

We analyze the statistics of the isotopes lighter and heavier than the iron group nuclei separately because the nuclei above \( A = 60 \) are mostly produced by the \( s \)-process. Above \( A = 90 \), the synthesis of the \( s \)-process is generally attributed to asymptotic giant branch (AGB) stars as are \( ^{12}\text{C} \) and \( ^{14}\text{N} \). Most of the iron group is probably made in Type Ia supernovae. The means and standard deviations of the production factors for nuclei below and above \( A = 60 \) that are attributed to massive stars are tabulated separately in Table 2. See also Figure 4.

3.1. The Production of Carbon, Oxygen, and Intermediate Mass Elements

When studying the nucleosynthesis of massive stars, theorists often normalize to the production of \( ^{16}\text{O} \), as it is the third most abundant isotope in the universe and comes almost entirely from massive stars (Langer 1996). For reference, we have included the production factor of \( ^{16}\text{O} \) in Table 2 as well.

In Figure 3, we compare the production factor of various elements to that of \( ^{16}\text{O} \) for variable \( M_{BH} \). For our present purposes, success is defined as being within a factor of two of the solar abundances. We use a number of alpha elements to probe the strength of the oxygen and silicon burning, and we use \( ^{12}\text{N} \) to measure the strength of the CNO cycle. From this, it is clear that little is lost in terms of the production ratios of these common isotopes if the upper mass limit is reduced from 120 to 40 \( M_\odot \), which supports the preliminary limits set by Heger et al. (2003).

However, for reduced upper mass limits, \( ^{12}\text{C} \) is overproduced in the winds compared to \( ^{16}\text{O} \), suggesting either that this bound cannot be much lower than 25 \( M_\odot \) (a production factor of
two) or that there is significantly less mass loss than assumed. For the mass range considered, carbon is mostly made in the winds of very massive stars, especially during their Wolf–Rayet stage. Room must also be left for the production of carbon in lower mass stars, which is also thought to be substantial. Results also depend upon the rate employed for the $^{12}$C($\alpha$, $\gamma$)$^{16}$O reaction rate. Here, a value 1.2 times that of Buchmann (1996) is employed, corresponding to an $S$-factor at 300 keV of 175 keV b, well within the current error bar (Schürmann et al. 2012). Oxygen, which is the major part of the metallicity, is also made in winds but more in the explosions. Their ratio then is quite sensitive to the mass loss prescription used. To illustrate this, in Figure 3, we have also included the ratios for a population for which we have halved the mass loss yields. In the figure, it is apparent that the C/O ratio remains consistent with the solar abundances down to an upper mass limit of about 20 $M_\odot$. To illustrate the change in the nucleosynthesis between the upper mass limit extrema, we present Figure 4 as a comparison to Figure 2. The apparent large overproduction of $^{40}$K in both figures is not a problem because $^{40}$K is radioactive with a half life of $1.26 \times 10^9$ years (Lide 2009). Much of it will decay before being incorporated into the Sun. The large yield of $^{22}$Ne remains a concern however. This yield can also be reduced if the mass loss is lower.

We have checked other important intermediate mass isotope ratios in order to probe how well these stellar populations represent the solar abundances. These include $^{28}$Si/$^{40}$Ca, $^{40}$Ca/$^{24}$Mg, $^{28}$Si/$^{56}$Fe, and $^{40}$Ca/$^{56}$Fe. As can be seen in Figure 5, these all remain acceptably close to solar ratios for the entire range of $M_{BH}$ and, perhaps surprisingly, are not tight constraints on $M_{BH}$.

### 3.2. The Supernova Rate

Using the production factor of $^{16}$O, we can estimate how the supernova rate depends upon $M_{BH}$. An accurate calculation of the rate itself would require a galactic chemical evolution model that includes gas accretion onto and outflows from the galactic disk—as described in Timmes et al. (1995)—and is beyond the scope of this paper. However, we can estimate the factor by which the supernova rate would have to increase by examining $N_{SN}$, the total number of massive stars required to die to produce the correct amount of $^{16}$O, normalized to the total number required to produce the yields of our control population ($M_{BH} = 120 M_\odot$). The number of stellar deaths (and therefore, supernovae) increases slowly with the lowering of the upper mass limit until approximately 40 $M_\odot$, below which it increases rapidly up to twice the original number at 28 $M_\odot$ and three times the original number at 19 $M_\odot$ (see Table 2).
3.3. The Light s-Process

The heavier component of the s-process, those nuclei above \( A \approx 90 \), is thought to be produced in low mass stars (Pignatari et al. 2010). The production of the light component of the s-process, on the other hand, is generally attributed to massive stars and occurs late during helium burning when the temperature rises sufficiently for the \( ^{22}\text{Ne}(\alpha, n)\ )^{25}\text{Mg} \) reaction to occur. Owing to the temperature sensitivity of this rate, production of the s-process isotopes in the mass range \( A = 60 – 90 \) is a potentially powerful constraint on \( M_{\odot} \). It is important that we overproduce the s-process elements somewhat in this stellar mass range as many of the primary isotopes are also made in lower metallicity stars that do not produce many s-process elements.

Use of this diagnostic is complicated by the fact that many isotopes in the mass range \( A = 60 – 90 \) can be produced by both the s- and r-processes, and so an alternative approach is to focus on a few “s-only” isotopes (Figure 6)—those isotopes produced exclusively by the s-process—\( ^{70}\text{Ge}, ^{76}\text{Se}, ^{80}\text{Kr}, \) and \( ^{87}\text{Sr} \) (Kappeler et al. 1989). We exclude \( ^{80}\text{Kr} \) and \( ^{82}\text{Kr} \) from our analysis—despite both being s-only isotopes—as these isotopes are also significantly produced in low-mass AGB stars. We notice that the s-process is most predominant in core-collapse supernovae from 30 to 50 \( M_{\odot} \). With more complex models of the stellar population, a comparison of the total s-process yields to the solar abundance could prove to provide greater insight as to the upper mass bound. Here, we see that \( ^{80}\text{Sr} \) and \( ^{87}\text{Sr} \) are underproduced regardless of the upper bound, which is expected, as these isotopes are also produced in AGB stars (Arlandini et al. 1999). However, the other isotopes, \( ^{70}\text{Ge} \) and \( ^{76}\text{Se} \), are produced primarily in massive stars. The production of \( ^{70}\text{Ge} \) falls below 1/2 the solar abundance at 21 \( M_{\odot} \), whereas the production of \( ^{87}\text{Sr} \) falls below 1/2 solar production at 23 \( M_{\odot} \). However, if we increase the rate of \( ^{22}\text{Ne}(\alpha, n) \) to the maximum experimental value according to Jaeger et al. (2001), we find that a limit of 18 \( M_{\odot} \) is a reasonable value for the mass of the heaviest supernovae.

It is important to note here that this result depends heavily on the \( ^{22}\text{Ne}(\alpha, n)\ )^{25}\text{Mg} \) rate, as can be seen in Figures 6 and 7. The values for this rate used in the present study are taken from Jaeger et al. (2001). For calibration, the “normal” value at \( 3 \times 10^{8} \) K is \( 2.58 \times 10^{-11} \text{ cm}^{3} \text{ s}^{-1} \) and the “high” value is \( 3.14 \times 10^{-11} \text{ cm}^{3} \text{ s}^{-1} \). More recent studies of this reaction rate by Longland et al. (2012) suggest that an even higher value may not be unreasonable, extending up to perhaps as much as \( 4.1 \times 10^{-11} \text{ cm}^{3} \text{ s}^{-1} \). To explore this extreme possibility, we also carried out runs in which the Jaeger et al. (2001) “normal” rate was multiplied by two. These three cases are labeled in the figures as “Normal,” “High,” and “X2.” In all cases, we used the “low” value from Jaeger et al. (2001) for the \( ^{22}\text{Ne}(\alpha, \gamma)^{26}\text{Mg} \) rate, which corresponds to \( 0.81 \times 10^{-11} \text{ cm}^{3} \text{ s}^{-1} \) at \( 3 \times 10^{8} \) K. It is clear from Figures 6 and 7 that both the production of the s-only elements and of the light s-process as a whole are only improved by increasing this rate.

3.4. \( ^{60}\text{Fe} \) and \( ^{26}\text{Al} \)

The nuclei \( ^{60}\text{Fe} \) \( (\tau_{1/2} = 2.62 \times 10^{6} \text{ yr}) \) and \( ^{26}\text{Al} \) \( (\tau_{1/2} = 7.17 \times 10^{5} \text{ yr}) \) are interesting because they accumulate in the interstellar medium where the emission generated by their decays can be studied using gamma-ray telescopes. Observations by Wang et al. (2007) give a ratio for the decay rate of \( ^{60}\text{Fe} \) to that of \( ^{26}\text{Al} \) of about 0.148, implying a ratio of \( ^{60}\text{Fe} \) to \( ^{26}\text{Al} \) mass fractions of \( (60/26)/(0.148) = 0.34 \) (Woosley & Heger 2007). As pointed out by Prantzos (2004) and discussed in Woosley & Heger (2007), current calculations give a larger value. As Figure 8 shows, our mass-averaged estimate of the production is 1.15 for \( M_{\odot} = 120 \). This compares favorably with the value 0.95 given for these models by Woosley & Heger (2007).

The remaining difference between our mass ratio and 0.34 probably chiefly reflects the remaining uncertainty in the neutron capture cross sections for \( ^{56}\text{Fe} \) and \( ^{26}\text{Al} \), the treatment of semiconvection, mass loss and rotation in the models, and the choice of explosion energies for low mass supernovae. Studies of the light curves of Type IIp supernovae (Kasen & Woosley 2009) suggest that many supernovae, perhaps most, have an explosion energy smaller than the fiducial \( 1.2 \times 10^{51} \text{ erg} \) assumed in many studies. Reducing the explosion energy reduces the yield of \( ^{60}\text{Fe} \).
substantially. Limongi & Chieffi (2006) have also emphasized the dependence of this production ratio on mass loss, convection theory, and the initial mass function. Including the effects of rotation may also increase the $^{26}\text{Al}$ yield (Palacios et al. 2005), especially in very massive stars.

Our purpose here is not to completely resolve the debate surrounding $^{60}\text{Fe}^{26}\text{Al}$ but to point out that the answer depends upon $M_{\text{BH}}$. Measurements of gamma-ray line flux ratios may thus ultimately help constrain the masses of stars that explode. Figure 8 shows that the ratio of $^{60}\text{Fe}^{26}\text{Al}$ produced by supernovae declines as $M_{\text{BH}}$ becomes smaller. Given that the production of $^{60}\text{Fe}$ will be even smaller in those stars we are assuming still explode if their kinetic energy is reduced, this effect could reduce the average production of $^{60}\text{Fe}$ appreciably.

### 3.5. Helium Production and $\Delta Y/\Delta Z$

As discussed extensively in Maeder (1992), the measured derivative of the helium mass function with respect to metallicity can, in principle, be used to constrain $M_{\text{BH}}$. This is because the winds of the most massive stars are rich in helium while the heavy elements are largely confined to the cores. If the cores collapse to black holes, trapping the heavy elements, then the synthesis of the winds remains and increases the overall average of $\Delta Y/\Delta Z$. Observations suggest a value $\Delta Y/\Delta Z \sim 4$ (Pagel et al. 1992).

In practice, the application of this metric is fraught with uncertainty. The yields of the massive stars are dependent upon the initial mass function and especially the very uncertain mass loss rates employed. After the helium core is uncovered by mass loss, Wolf–Rayet mass loss contributes not only helium, but an increasing amount of carbon and oxygen. The remnant masses depend upon an uncertain explosion mechanism. Does all of the presupernova star fall into the hole or only part? For successful explosions, where is the mass cut? Lower mass stars also contribute appreciably to both helium and metallicity and the yields of stars of all masses are sensitive to metallicity. Even an approximate result requires integration over some uncertain model for galactic chemical evolution.

However, because this metric has been applied extensively in the literature, we give in Figure 9 our results for the solar metallicity stars considered in this survey. Until $M_{\text{BH}}$ is reduced below $\sim 40 M_\odot$, $\Delta Y/\Delta Z$ remains slightly less than unity. Even for $M_{\text{BH}} = 18 M_\odot$, $\Delta Y/\Delta Z$ is still only 1.9, well below the observed value.

These results are, at first glance, seemingly inconsistent with those of Timmes et al. (1995) who found $\Delta Y/\Delta Z = 4$ for $M_{\text{BH}} = 17 M_\odot$ for solar metallicity stars and $30 M_\odot$ for low metallicity stars. However, Timmes et al. used the survey of Woosley & Weaver (1995) which included only stars below $40 M_\odot$, while our grid extends to 120 $M_\odot$. Furthermore, Timmes et al. assumed that any winds would be metal free and not extend into the helium core. We include initial metals in the envelope and mass loss from Wolf–Rayet stars once the core is uncovered. If we redo our calculation using the assumptions of Timmes et al., then the dashed curve in Figure 9 results. This curve crosses $\Delta Y/\Delta Z$ at $M_{\text{BH}} = 17 M_\odot$, in excellent agreement with Timmes et al. However, we believe that our results for solar metallicity are more realistic and that a lower value of $\Delta Y/\Delta Z$ from massive stars is appropriate.

### 3.6. Average Mass of Compact Remnants

Zhang et al. (2008) calculated fall back and black hole production in the same supernovae employed in the present study, and one can use their results to estimate the properties of the compact remnants left by solar metallicity stars as a function of $M_{\text{BH}}$. Their Table 4 gives the baryonic masses of the remnants for our fiducial set for stars, the “sA Models.” Results are given for initial masses from 12 to 100 $M_\odot$. To these we add the remnant masses specified in their text: 1.37 $M_\odot$ for the remnant of an 11 $M_\odot$ star and 1.35 $M_\odot$ for a 10 $M_\odot$ star. The gravitational mass for the resulting neutron stars, where one forms, can be calculated using their Equation (2). It is assumed that the maximum gravitational mass of a neutron star is $2.0 M_\odot$ so all remnants with a baryonic mass over 2.35 $M_\odot$ form black holes with a gravitational mass equal to its initial baryonic mass. Once again assuming a Salpeter initial mass function, the average properties of the remnants can be determined as a function of $M_{\text{BH}}$, the heaviest supernova mass.

Figure 10 shows the resulting average black hole mass, neutron star mass, iron core mass, and the maximum remnant mass as a function of $M_{\text{BH}}$. For those stars more massive than the heaviest supernova, we have assumed that the presupernova star collapses completely to a black hole, so our black hole masses are larger than those of Zhang et al. (2008). The results can be compared with the observed average neutron star mass from Schwab et al. (2010). From 14 neutron stars with well-measured masses, they find an average neutron star mass of 1.4 $M_\odot$.
of 1.325 ± 0.056 \(M_\odot\). We find an average neutron mass closest to this at 14 \(M_\odot\) and are within their uncertainty up to 16 \(M_\odot\). This suggests that a low value for \(M_{\text{BH}}\) is more consistent with the observed neutron star masses. However, there are appreciable errors in both the observational limits and the remnant masses calculated by Zhang et al. In fact, any of the neutron star masses plotted in Figure 10 is not badly discrepant with observations.

The maximum and average black hole masses are a more sensitive indicator of \(M_{\text{BH}}\). Substantially larger values result if \(M_{\text{BH}}\) is low. Interpretation of these results is complicated though by our uncertain knowledge of both mass loss and the explosion mechanism. Lower metallicity stars would presumably experience less mass loss and die with higher masses, potentially producing larger black holes. On the other hand, even a weak explosion might eject part of the presupernova star.

4. CONCLUSIONS

By examining a variety of nucleosynthetic diagnostics, one can constrain the mass of the maximum mass supernova that must explode and not swallow up its heavy elements in a black hole. At the outset, a number of caveats are worth stating. At the outset, a number of caveats are worth stating.

Given these limitations, the best we can say at the present time is what supernova mass limits might be consistent with observations. The idea of a limiting mass is itself an approximation, since the compactness of the core is not a monotonic function of main sequence mass (O’Connor & Ott 2011), especially in the interesting range 20–35 \(M_\odot\). For still heavier stars, mass loss may shrink the helium core so much that the presupernova helium core mass of say a 100 \(M_\odot\) star differs little from that of a 20 \(M_\odot\) star. Such massive stars are rare, however, and their nucleosynthesis is mostly due to their presupernova winds.

We have looked at several processes that limit \(M_{\text{BH}}\). As \(M_{\text{BH}}\) is decreased, the necessary rate of “successful” supernovae rises. For \(M_{\text{BH}} = 20\) the rate is 2.88 times greater than for \(M_{\text{BH}} = 120\). Surprisingly, in reducing \(M_{\text{BH}}\) to 20 \(M_\odot\), the overall nucleosynthesis of most isotopes from Ne to Ca with respect to 16O is altered little, and the production of some isotopes in the iron group is actually improved. The greatest apparent problem is 22Ne; however, this can be mitigated somewhat by reducing the amount of mass loss by increasing the 22Ne(\(\alpha, n\)) rate. Of the s-only isotopes produced mainly in massive stars, 70Ge becomes the limiting isotope for the mass of the heaviest supernova, reaching half of solar value at 23 \(M_\odot\). This can be extended to 18 \(M_\odot\) by increasing the 22Ne(\(\alpha, n\)) rate.

In total, we find that we can easily reduce the mass of the heaviest supernovae to 40 \(M_\odot\) without any significant changes. For KEPLER’s standard values of nuclear rates and mass loss, there are only moderate changes in these processes down to 25 \(M_\odot\). The limits become increasingly severe for smaller masses. For \(M_{\text{BH}} = 25\ M_\odot\), the stellar winds overproduce 12C with respect to 16O by a factor of two, unless we reduce the mass loss in these stars by two. At \(M_{\text{BH}} = 21\ M_\odot\), the lighter elements are overproduced in these more massive stars, and the s-process produces only half the needed 70Ge unless the 22Ne(\(\alpha, n\))25Mg rate is increased. At 20 \(M_\odot\), even with halved mass loss, the winds overproduce 12C by a factor of two. At 19 \(M_\odot\), the supernova rate is three times what it would have been had all stars contributed their full nucleosynthesis.

We are grateful to Frank Timmes for very helpful correspondence concerning the calculation of \(\Delta Y/\Delta Z\). This research has been supported at UCSC by the National Science Foundation (AST 0909129) and the NASA Theory Program (NNX09AK36G). J.B. also received support from the University of California Regent’s Fellowship Program. This research is supported in part by the Department of Energy Office of Science Graduate Fellowship Program (DOE SCGF), made possible in part by the American Recovery and Reinvestment Act of 2009, administered by ORISE-ORAU under contract No. DE-AC05-06OR23100.

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