Supernova Nucleosynthesis in Massive Stars

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Presupernova evolution and explosive nucleosynthesis in massive stars for main-sequence masses from 13 $M_\odot$ to 70 $M_\odot$ are calculated. We examine the dependence of the supernova yields on the stellar mass, $^{12}C(\alpha, \gamma)^{16}O$ rate, and explosion energy. The supernova yields integrated over the initial mass function are compared with the solar abundances.

1. Presupernova models and the $^{12}C(\alpha, \gamma)^{16}O$ rate

Presupernova models are obtained for helium stars with masses of $M_\alpha = 3.3$, 4, 5, 6, 8, 16, and 32 $M_\odot$ as an extension of the studies by Nomoto & Hashimoto (1988), Thielemann et al. (1993), and Hashimoto et al. (1993). These helium star masses correspond approximately to main-sequence masses of $M_{ms} = 13$, 15, 18, 20, 25, 40, and 70 $M_\odot$, respectively (Sugimoto & Nomoto 1980). The systematic study for such a dense grid of stellar masses enables us to understand how explosive nucleosynthesis depends on the presupernova stellar structure and to apply the results to the chemical evolution of galaxies. We use the Schwarzschild criterion for convection and neglect overshooting. The initial composition is given by $X(^4He) = 0.9879$ and $X(^{14}N) = 0.0121$. These helium stars are evolved from helium burning through the onset of the Fe core collapse.

Nuclear reaction rates are mostly taken from Caughlan & Fowler (1988). For the uncertain rate of $^{12}C(\alpha, \gamma)^{16}O$, we use the rate by Caughlan et al. (1985; CFHZ85), which is larger than the rate by Caughlan & Fowler (1988; CF88) by a factor of ~ 2.4. To examine the influence of this difference, we evolve the $M_\alpha = 8$ $M_\odot$ helium star, using the $^{12}C(\alpha, \gamma)^{16}O$ rate by CF88 (case 25B). [The 25 $M_\odot$ star model with the $^{12}C(\alpha, \gamma)^{16}O$ rate by CFHZ85 is denoted as case 25A.] At the end of core helium burning, the formation of the carbon-oxygen core and its composition are influenced largely by the $^{12}C(\alpha, \gamma)^{16}O$ rate. The larger rate results in a smaller C/O ratio, which affects the abundances of Ne, Mg, Al relative to O in the more evolved cores.

Comparison of the presupernova density structures for the two cases 25A and 25B shows that case 25B has a more concentrated core at $M_r < 2M_\odot$ (i.e., a steeper density gradient) and more extended outer layers than case 25A. This is due to a larger carbon abundance and thus stronger carbon shell burning in case 25B.

It is found that the size of the iron core is not a monotonic function of the helium core mass as shown by Barkat & Marom (1990) and Woosley (1993). For $M_{ms} = 13$, 15, 18, 20, 25 (case 25A), 40, and 70 $M_\odot$, the iron core masses are 1.18, 1.28, 1.36, 1.40, 1.42, 1.88, and 1.57 $M_\odot$, respectively. In case 25B, the iron core mass is 1.37 $M_\odot$, which is smaller than in case 25A.

2. Explosive nucleosynthesis

The hydrodynamic phases of supernova explosions for the above eight presupernova models were followed with an extensive nuclear reaction network (Hashimoto *et al.* 1989, 1993; Thielemann *et al.* 1990, 1993).

Since the mechanism of supernova explosions after core collapse is not fully understood yet, the explosion energy and the mass cut (or ^{56}Ni mass) have remaining uncertainties, except for SN 1987A. The final kinetic energy of the explosion is assumed to be $E = 1.0 \times 10^{51}$ erg as inferred from the modeling of SN 1987A and SN 1993J (e.g., Shigeyama & Nomoto 1990; Shigeyama *et al.* 1994).

In the present study, the mass cut is chosen to produce 0.075 $M_\odot$ ^{56}Ni for 13 – 70 $M_\odot$ stars. This is based on the estimates from the light curves of SN 1993J for the 13 – 15 $M_\odot$ stars (e.g., Nomoto *et al.* 1993; Wheeler & Filippenko 1993) and SN 1987A for the 18 – 20 $M_\odot$ stars (e.g., Nomoto *et al.* 1993). For more massive stars, a similar mass of ^{56}Ni is suggested from SN 1990E (Schmidt *et al.* 1993) and also from the absence of very bright type Ib supernovae with slow decline (e.g., Shigeyama *et al.* 1990).

Figures 1 and 2 show the integrated abundances of the ejecta relative to the solar values (Anders & Grevesse 1989) for $M_{\rm ms} = 13$, 15, 18, 20, 40, and 70 $M_\odot$, respectively. Figure 3 shows three cases of $M_{\rm ms} = 25$ $M_\odot$, i.e., cases 25A, 25B, and 25BE (see below).
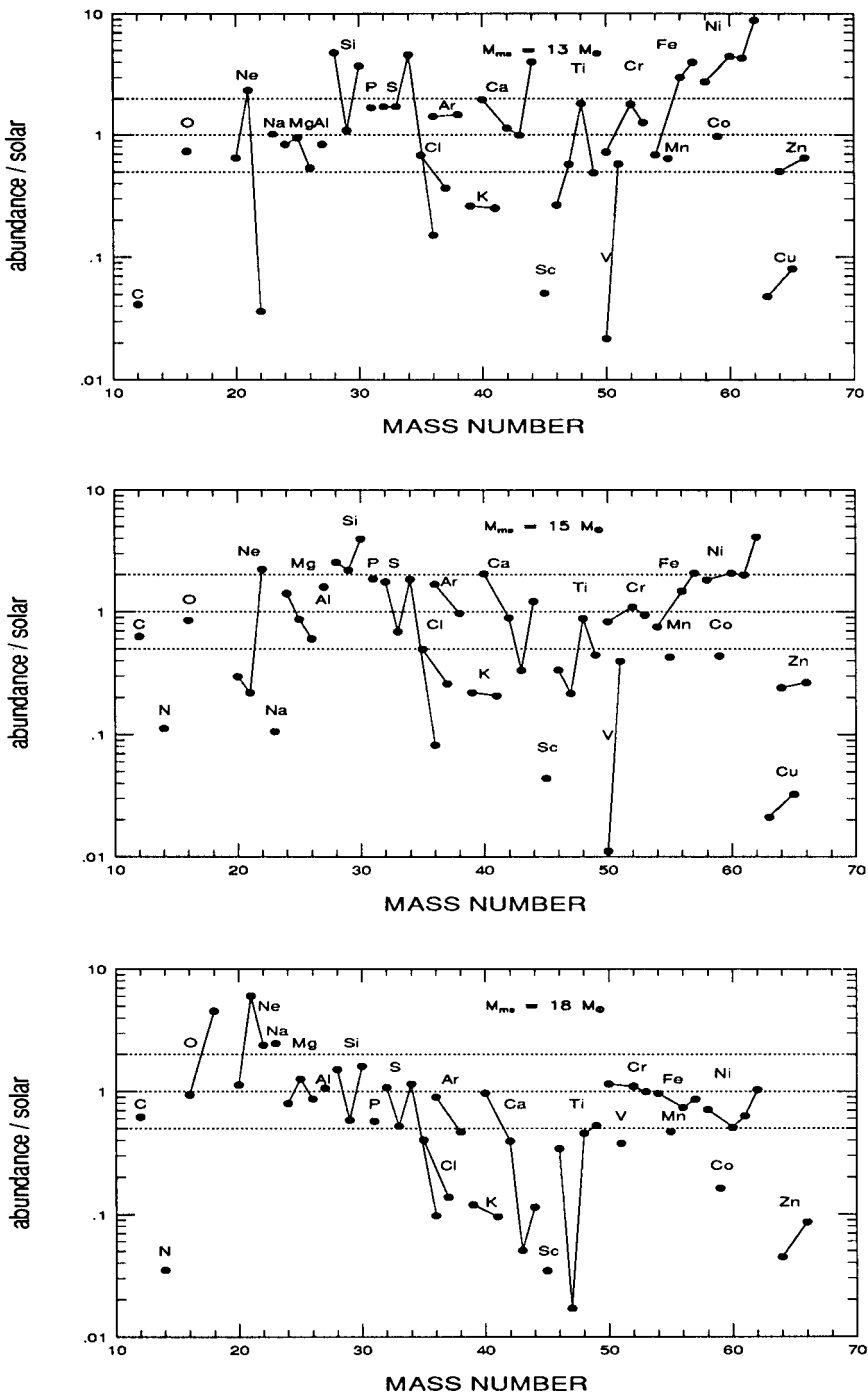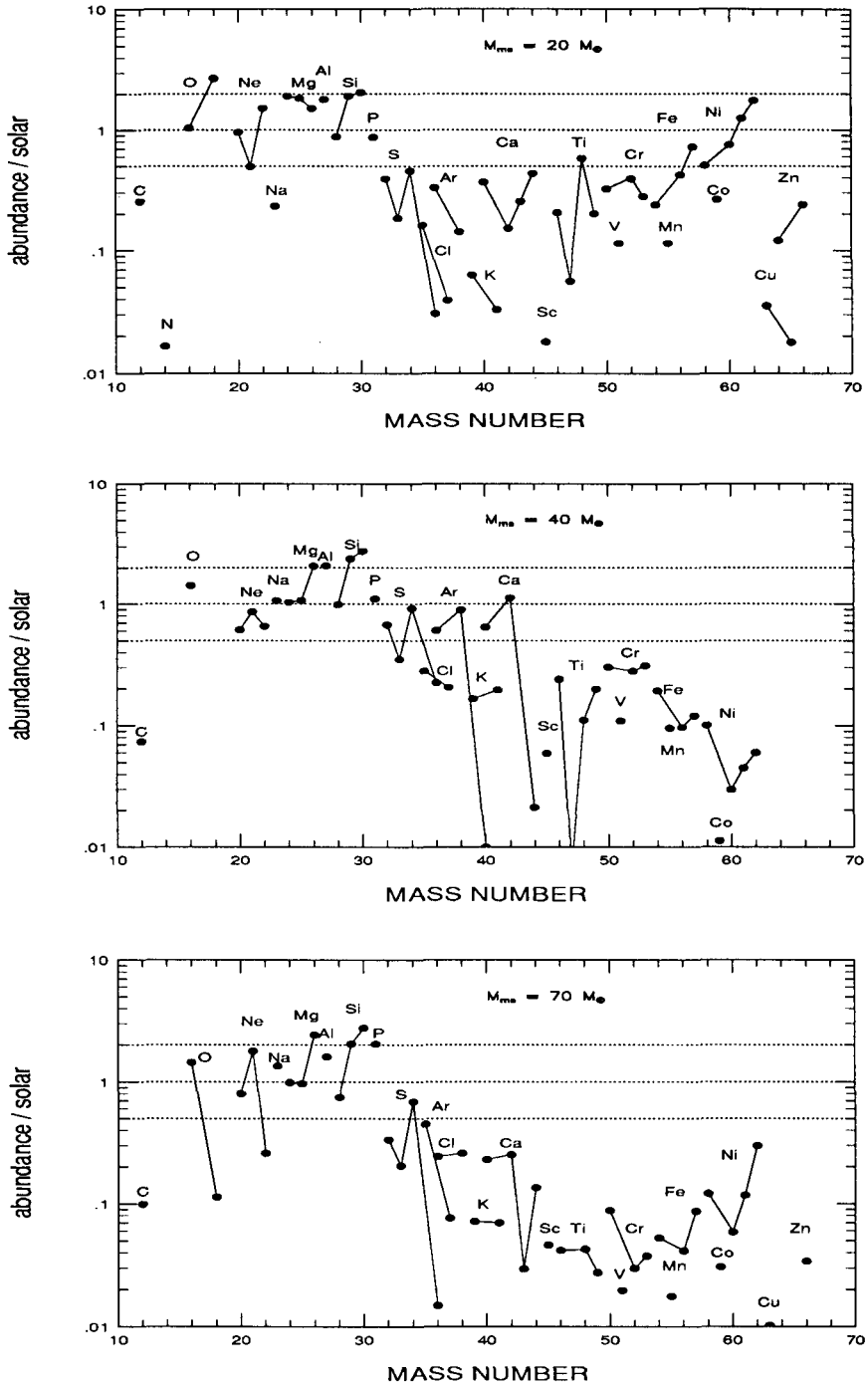
FIGURE 1. Abundances of stable isotopes relative to the solar values for the 13, 15, and 18 $M_\odot$ stars.

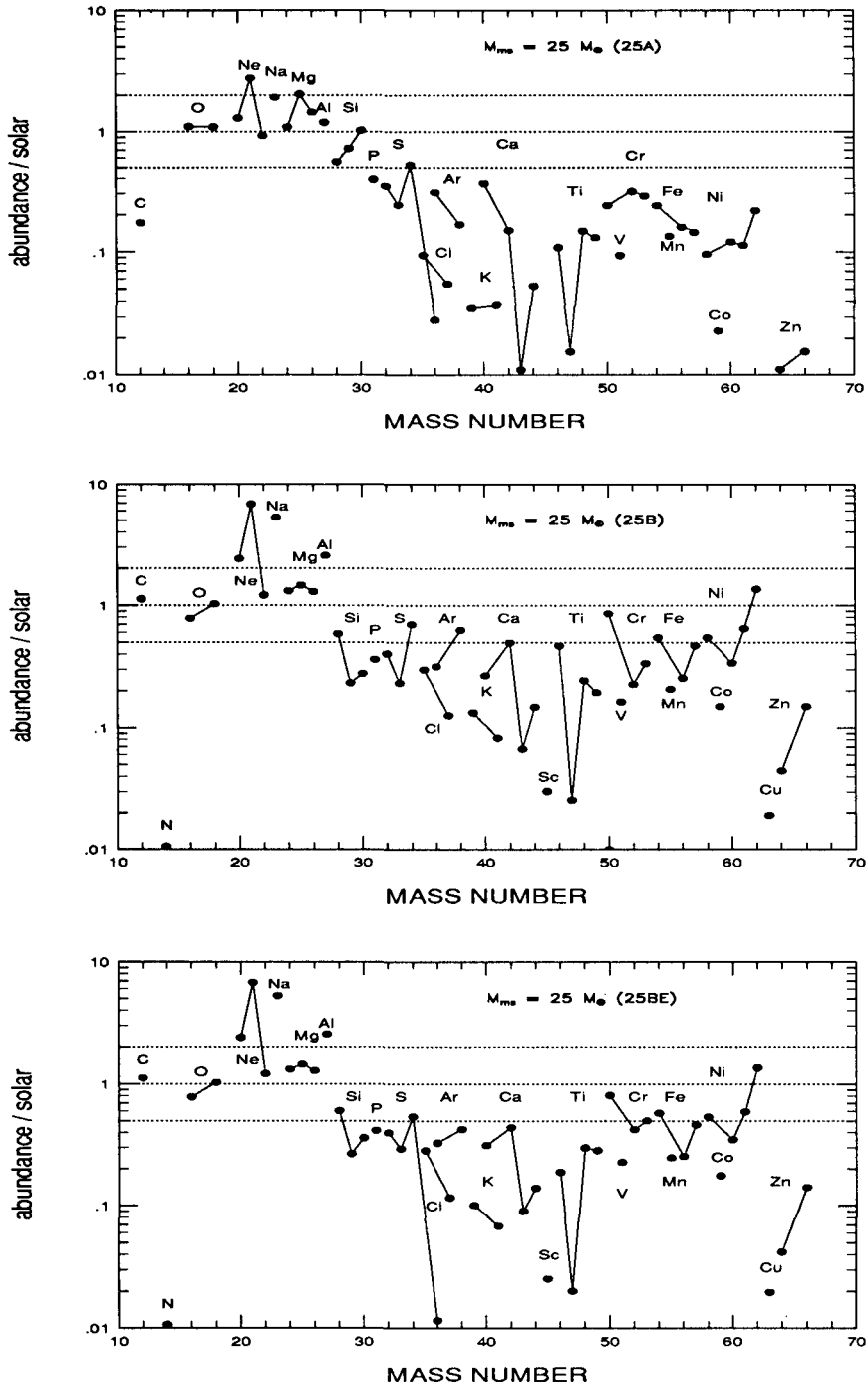FIGURE 2. Same as Fig. 1 but for the 20, 40, and 70 $M_\odot$ stars.

FIGURE 3. Same as in Fig. 1 but for the 25 $M_\odot$ star (case 25A). Case 25B uses the $^{12}C(\alpha,\gamma)^{16}O$ rate by CF88 and case 25BE is the same as 25B but with $E = 1.5 \times 10^{51}$ erg s^{-1}.
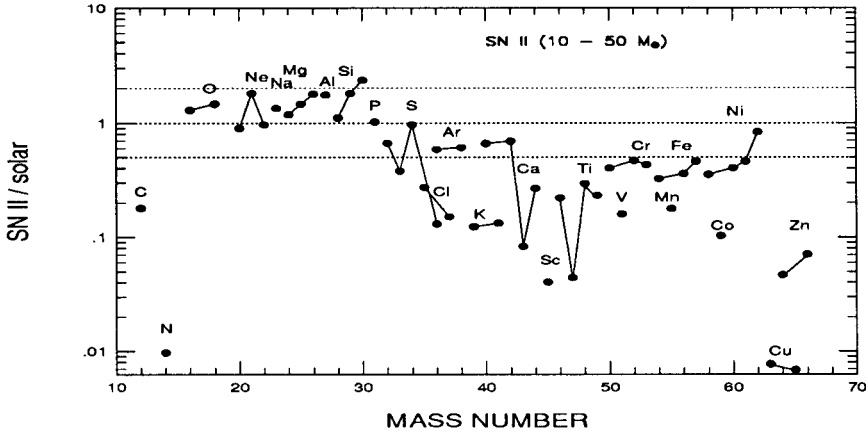
FIGURE 4. Nucleosynthesis products from $10 - 50$ $M_\odot$ stars averaged over the IF relative to solar abundances.

TABLE 1. Nucleosynthesis products (in $M_\odot$) from $10 - 50$ $M_\odot$ stars averaged over the IMF.

^{12}C	7.93E-02	^{35}Cl	1.01E-04	^{54}Cr	1.83E-08
^{13}C	3.80E-09	^{37}Cl	1.88E-05	^{55}Mn	3.44E-04
^{14}N	1.56E-03	^{36}Ar	6.62E-03	^{54}Fe	3.38E-03
^{15}N	1.66E-08	^{38}Ar	1.37E-03	^{56}Fe	6.10E-02
^{16}O	1.80	^{40}Ar	2.27E-08	^{57}Fe	1.92E-03
^{17}O	9.88E-08	^{39}K	6.23E-05	^{58}Fe	6.43E-09
^{18}O	4.61E-03	^{41}K	5.07E-06	^{59}Co	5.01E-05
^{19}F	1.16E-09	^{40}Ca	5.77E-03	^{58}Ni	2.54E-03
^{20}Ne	2.12E-01	^{42}Ca	4.23E-05	^{60}Ni	1.15E-03
^{21}Ne	1.08E-03	^{43}Ca	1.08E-06	^{61}Ni	5.76E-05
^{22}Ne	1.83E-02	^{44}Ca	5.53E-05	^{62}Ni	3.37E-04
^{23}Na	6.51E-03	^{46}Ca	1.43E-10	^{64}Ni	3.18E-14
^{24}Mg	8.83E-02	^{48}Ca	5.33E-14	^{63}Cu	6.45E-07
^{25}Mg	1.44E-02	^{45}Sc	2.29E-07	^{65}Cu	2.65E-07
^{26}Mg	2.01E-02	^{46}Ti	7.19E-06	^{64}Zn	6.76E-06
^{27}Al	1.48E-02	^{47}Ti	1.34E-06	^{66}Zn	6.06E-06
^{28}Si	1.05E-01	^{48}Ti	9.23E-05	^{67}Zn	1.19E-08
^{29}Si	8.99E-03	^{49}Ti	5.55E-06	^{68}Zn	2.73E-09
^{30}Si	8.05E-03	^{50}Ti	2.95E-10	^{69}Ga	2.60E-12
^{31}P	1.21E-03	^{50}V	6.19E-10	^{71}Ga	1.37E-14
^{32}S	3.84E-02	^{51}V	8.73E-06	^{70}Ge	1.65E-12
^{33}S	1.78E-04	^{50}Cr	4.34E-05	^{72}Ge	1.61E-12
^{34}S	2.62E-03	^{52}Cr	1.01E-03	^{73}Ge	9.25E-17
^{36}S	1.78E-06	^{53}Cr	1.08E-04		

To examine the dependence on the explosion energy, we show the case 25BE, i.e., case 25B with $E = 1.5 \times 10^{51}$ erg. The larger explosion energy leads to the outward shift of the abundance distribution. This leads to minor differences between the abundances for the two explosion energies (Fig. 3).

3. Isotopic abundance ratios

Figure 4 shows the isotopic abundances relative to their solar values (Anders & Grevesse 1989) after averaging over the mass range from 10 to 50 $M_\odot$ with an initial mass function $\propto M^{-1.35}$. Here the upper mass limit 50 $M_\odot$ is chosen from the comparison of [O/Fe] and [Mg/Fe] with those of metal-poor stars (Tsujimoto *et al.* 1994). We also assume no heavy element production below 10 $M_\odot$ and approximate the abundances of 10 – 13 $M_\odot$ stars by a linear interpolation between 10 and 13 $M_\odot$. Table 1 gives the integrated masses ($M_\odot$) of stable species averaged over the initial mass function.

Figure 4 shows that the relative abundance ratios from massive stars are in good agreement with the solar ratios for $A < 27$. [The sum of type Ia and type II products with a ratio of 1 to 9 reproduces well the solar abundances for a wider range of A (Tsujimoto *et al.* 1993).] Note that this agreement is realized for the $^{12}C(\alpha,\gamma)^{16}O$ rate by CFHZ85, i.e., case 25A. For case 25B, Ne, Na, and Al relative to O are overproduced with respect to the solar ratios as seen in Figure 3. This is due to the larger C/O ratio in case 25B after helium burning. Since the products of the 25 $M_\odot$ star dominate type II supernova yields, this result suggests that the $^{12}C(\alpha,\gamma)^{16}O$ rate is higher than that of CF88 and closer to CFHZ85. The presently most reliable experimental investigations give values in between the two rates.

We should note that the isotopic ratios in Figures 1 – 4 depend not only on the $^{12}C(\alpha,\gamma)^{16}O$ rate but also on convective overshooting, mixing fresh He into the core at late high temperature core helium burning stages. The above comparison that favors the CFHZ85 rate is based on the calculations with no convective overshooting. If overshooting during convective core helium burning would reduce the C/O ratio, a smaller $^{12}C(\alpha,\gamma)^{16}O$ rate would be favored (Weaver & Woosley 1993).

Figure 4 also shows that some species, ^{35}Cl, ^{39}K, ^{44}Ca, ^{48}Ti, and ^{59}Co, are underproduced relative to the solar values. If we include the weak component of the s-process nuclei $50 < A < 100$ produced during core helium burning (Prantzos *et al.* 1990), ^{48}Ti and ^{59}Co are enhanced appreciably compared with the seed (solar) abundances. ^{35}Cl, ^{39}K and ^{44}Ca are enhanced only by a factor of ~ 2. Synthesis of s-process elements during carbon shell burning would also be significant (Raiteri *et al.* 1993).

Acknowledgements

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