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Nucleosynthesis yields from different mass stars*

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Abstract Stellar nucleosynthesis yield is a vital factor of galactic chemical evolution model. With different yields, various evolutionary behavior of elements can be predicted, hence different scenarios of galactic chemical evolution can be shown. Investigators calculated different yields adopting different parameters of stellar evolution and nucleosynthesis. The corresponding parameters and the resulting yields of elements are compared for low-, intermediate-mass stars and massive stars, so that these analyses can provide valuable information and guidance to stellar nucleosynthesis and galactic chemical evolution studies.

Keywords: nucleosynthesis, yields, galactic chemical evolution, different mass stars.

Nucleosynthesis yields of stars are vital to exploring the chemical evolution history of galaxies. Among the three main ingredients required to follow the galactic chemical evolution (GCE), only one, namely the stellar nucleosynthesis yields, can be obtained from the firsthand calculation at present, while the other two, initial mass function (IMF) and star formation rate (SFR), can only be evaluated by empirical methods. However, different yields can be obtained with different parameters in stellar evolution and nucleosynthesis calculations, hence different GCE scenarios can be exhibited. Thus, it is necessary to compare and analyze these different yields and the related parameters, so that some useful information and guidance to the stellar nucleosynthesis and GCE studies can be provided. Moreover, it is very necessary to distinguish the stars according to their different masses for the different evolution and synthesize various elements. For example, the massive single stars with $M > 8M_\odot$ produce and eject the main parts of oxygen and α element into interstellar medium (ISM); the low- and intermediate-mass single stars are the main sources of nitrogen and slow neutron-capture process (s-process) elements; while the binary stars synthesize most part of Fe element through type Ia supernova (SN Ia) explosion. In this paper, we analyze and compare the nucleosynthesis mechanism and yields of low-, intermediate-mass stars (LIMS) and massive stars.

The stars with $M < 0.9M_\odot$ do contribute materials to the ISM in our galaxy at present due to their long lifetimes (>15 Gyrs). Some investigators calculated the yields for the stars with mass $M > 0.9M_\odot$[1~10]. Generally, there are two definitions for yield: (i) total yield, $Y_i(M)$, represents the total mass ejected by a star of mass M in the form of isotope i (obviously $Y_i(M) > 0$), including the part obtained from ISM when it formed, defined by $Y_i^0(M)$, and the part produced by itself during evolution, defined by $y_i(M)$, (ii) net yield, $y_i(M)$, is the mass of the isotope i newly created by the star. Some investigators offered either total yield $Y_i(M)$[6,8] or net yield $y_i(M)$[1~5,7], while others worked out both the total and the net yields[10]. In general, numerical GCE models need the quantities $Y_i(M)$, while analytical models require the net yield $y_i(M)$, folded with a stellar IMF. In numerical GCE models, the net yield can be transferred into total yield using the equation $Y_i(M) = Y_i^0(M) + y_i(M) = (M - M_{\mathrm{rem}}) Y_i(t_0) + Mp_{iM}$, where t_0 is the age of our galaxy at which a star with mass M formed, M_{rem} the remnant mass of the star. p_{iM} is defined as the mass fraction of a star with mass M that has been newly synthesized as species i and then ejected.

1 Nucleosynthesis yields of low- and intermediate-mass single stars

The stars with main sequence mass $0.9M_\odot < M < 8M_\odot$ (or $0.9M_\odot < M < 6M_\odot$ when

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strong overshooting is considered) can produce C, N, O and s-process elements. When the stars evolve into AGB stages, the third dredge-up process can dredge up the synthesized s-process elements and ^{12}C isotopes from the He-intershell and bring them onto the surface of stars. Before the third dredge-up, the surface compositions of stars have been changed by the first and second dredge-up processes (the latter only occurs in intermediate mass stars). Also, mass loss, metallicity and hot bottom burning (HBB) process strongly affect evolution and nucleosynthesis of AGB stars[1,11].

Table 1 summarizes the main parameters adopted in the three groups of AGB stars nucleosynthesis calculations[1,4,5], where the upper mass limit of intermediate mass stars, M_{up}, adopted by Ref. [4], is $5M_{\odot}$, not the usual value of $8M_{\odot}$, due to the strong overshooting adopted. With respect to the prescriptions of $M_{\mathrm{c}}-L$ and $M_{\mathrm{c}}-T_{\mathrm{ip}}$ relations from Ref. [1], the notable improvement has been made in Refs. [4] and [5], in which the effect of metallicity is included, and λ is the efficiency of the third dredge-up process, $M_{\mathrm{c}}^{\mathrm{min}}$ the critical core mass for the beginning of the third dredge-up process. In fact, the Reimers prescription with $\eta \leqslant 1$[1] cannot produce the "super-wind" mass-loss rates measured in stars close to the AGB-tip luminosities, while the mass loss rates used by Refs. [4] and [5] can. Moreover, the overluminosity of AGB stars with HBB can trigger high mass-loss rate, thus favoring the onset of the superwind regime with consequent reduction in the TP-AGB lifetime. M_{HBB} is the core mass at which HBB is assumed to operate.

Fig. 1 shows the corresponding net yields of ^{12}C, ^{14}N and ^{16}O of Refs. [1,4,5]. In Ref. [1], $\alpha = 1.5$, $\eta = 1/3$ are adopted for intermediate mass stars, and 0.0, 1/3 for low mass stars; while in Ref. [4], $\alpha = 2.0$. The ordinate axis labels, "y" (in unit of $M_{\odot}$), refers to net yields of different mass stars. The results show that the calculated value of C yields of low mass and low metallicity ($Z = 0.004$) stars given by Ref. [4] is the hightes. One of the main reasons is that the core mass at the first thermal pulse is larger at low metallicities[11]; therefore, the amount of material dredged-up from the core to the envelope is substantially larger in initially low-Z AGB stars. Another reason is that mass loss is less efficient at lower Z, which corresponds to a longer TP-AGB lifetime, a greater number of third dredge-up events, and then a higher C yield. However, the decrease in C yields of intermediate mass stars may be caused by HBB process occurring at the base of the convective envelope due to the high temperature[1]. Thus the surface abundances of ^{13}C and ^{14}N are enhanced at the expense of ^{12}C and ^{16}O[1,11]. The intermediate mass stars with lower metallicity produce more nitrogen because HBB process is more efficient at lower Z, and the corresponding lower mass loss causes a longer duration of HBB. Using different parameters of stellar evolution and nucleosynthesis, Ref. [1] provided the higher N yields than that in Refs. [4] and [5], and the C yields in Ref. [5] are the lowest among the three groups. The positive net yields of O element of low mass stars is thank to the dredge-up events during the TP-AGB phase, whereas it becomes negative

Table 1 Summary of the main parameters adopted in the synthetic TP-AGB models[1,4,5]

	Ref. [1]	Ref. [4]	Ref. [5]
M_{up}	$8M_{\odot}$	$5M_{\odot}$	$8M_{\odot}$
Metallicities	$Z=0.004,\ 0.020$	$Z=0.004,\ 0.008,\ 0.020$	$Z=0.001\sim0.02$
$M_{\mathrm{c}}-L$ relation	No Z-dependence	Z-dependence	Z-dependence
$M_{\mathrm{c}}-T_{\mathrm{ip}}$ relation	No Z-dependence	Z-dependence	Z-dependence
Mass loss	Reimers[12], $\eta=1/3, 2/3$	See Ref. [13]	Reimers[12], $\eta=5$
The third dredge-up:			
λ	$0.3\sim0.5$, function of M_{c}	0.65 for $Z=0.004$; 0.55 for $Z=0.008$	0.75
$M_{\mathrm{c}}^{\mathrm{min}}$	$0.60\ M_{\odot}$	From envelope integrations Function of M and Z	$0.58\ M_{\odot}$
HBB:			
Overluminosity	No	Yes	No
Nucleosynthesis	Nuclear network	Nuclear network	Parameterized approx.
α value	0.00, 1.50, 2.00	1.68, 2.00, 2.50	$M_{\mathrm{HBB}}=0.8M_{\odot}$

at higher mass because of HBB. And the increasing positive trend with decreasing metallicities essentially reflects the longer duration of the TP-AGB phase. In addition, the yields given in Refs. [2, 3] are similar to those of Ref. [4]; the latter used the updated parameters and gave yields of the lower metallicity stars ($Z=0.004$), which is very important for the study of contributions of AGB stars to elements in early Galactic ages.

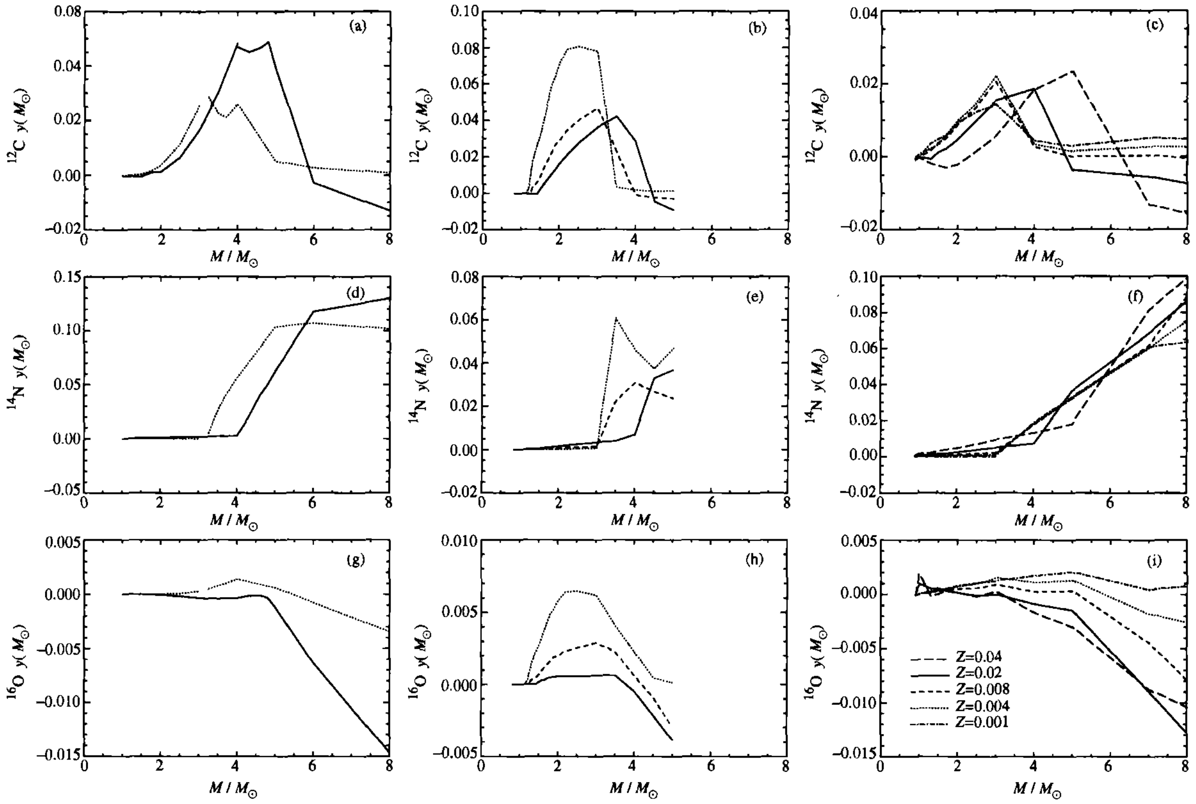

Fig. 1. Yields of ^{12}C, ^{14}N and ^{16}O isotopes of LIMS given in Refs. [1, 4, 5] as a function of the initial stellar mass. (a), (d) and (g) are taken from Ref. [1]; (b), (e) and (h) from Ref. [4]; (c), (f) and (i) from Ref. [5].

2 Nucleosynthesis yields of massive single stars

Stars with main sequence mass $8M_\odot < M < 11M_\odot$ (or $6M_\odot < M < 8M_\odot$ when strong overshooting is considered) generally develop a degenerate ONeMg core after C-burning, and eventually explode as "electron capture" supernova, expelling a very small quantity of heavy elements[6,10]. The explosion conditions are very complex, and only Ref. [10] gives the nucleosynthesis of $6M_\odot$ and $7M_\odot$ stars.

Stars with main sequence mass $M > 11M_\odot$ produce Fe core at the end of the evolution by hydrostatic Si-burning, and end their lifetime by the Fe core supernova explosion, which is known as SN Ⅱ explosion generally. SN Ⅱ explosion produces significant amounts of heavy elements, especially O and other α elements. Here we choose C, N, O and Fe elements as typical representatives to compare the different sets of nucleosynthesis yields.

2.1 Massive stars without stellar wind mass loss

Calculations of the nucleosynthesis of SN Ⅱ explosion were carried out by many investigators. Here we compared the results of Woosley[6] (model B) and Nomoto[8], which have been widely used in GCE models. Table 2 shows the main parameters used by those authors. Among these parameters, the important one is $^{12}C(\alpha, \gamma)^{16}O$ reaction rate. The higher the rate, the greater the extent to which carbon is converted into oxygen. The higher rate[15] adopted in Ref. [8] causes apparent low ^{12}C yields. Another difference is that Nomoto et al.[8] adopted the He core evolution instead of entire stars. Thus, they used

Table 2 Main parameters of the SN Ⅱ nucleosynthesis in Ref. [6] (model B) and Ref. [8]

	Ref. [6]	Ref. [8]
Initial mass	$(11\sim40)M_\odot$	$13\sim70M_\odot$
Metallicities	$Z=0, 10^{-4}$, 0.01, 0.1, $1Z_\odot$	$Z=Z_\odot$
$^{12}C(\alpha,\gamma)^{16}O$	1.7 × values of Ref. [14] ≈0.74 × values of Ref. [15]	values of Ref. [15] ≈2.3 × values of Ref. [14]
Explosion energy	1.2×10^{44} J $E\approx1.5\times1.2\times10^{44}$ J for $M\geqslant30\ M_\odot$	1.0×10^{44} J $E\approx1.5\times10^{44}$ J for $M\geqslant25M_\odot$
Convection	Ledoux criterion, Modification for semi-convection	Schwarzschild criterion, Convective shells have greater extension
Explosion mechanism	Piston situated at the Y_e discontinuity	Deposition of energy
Neutrinos	Nucleosynthesis caused by the flood of neutrinos	Neutrinos process not included
Stellar evolution	Entire stars	Helium cores

a relation $M(M_\alpha)$ to transfer the results of helium core of mass M_α to a scale of initial mass M. It can be understood that the total ejected mass of a certain element is given by the yield from the evolution of He core (M_α) plus the original element abundance in the envelope part with mass ($M - M_\alpha$)[1]. More details can be found in Ref. [8].

Fig. 2 shows the yields of ^{12}C, ^{14}N, ^{16}O and ^{56}Fe isotopes given in Refs. [6] and [8]. Only the yields of the stars with $(13\sim40)M_\odot$ in Ref. [8] are shown here. The ordinate axis labels "Y" (in unit of $M_\odot$) refer to the total yields of different mass stars. Fig. 2(a) shows that C yields given in Ref. [8] are lower than those of Ref. [6], which is mainly caused by adopting the higher $^{12}C(\alpha,\gamma)^{16}O$ reaction rate. N yields of low metallicity stars are very low. And a large amount of oxygen is produced by SN Ⅱ explosion, and O yields are higher for the higher mass stars. The Fe yields in Ref. [6] are extremely high, especially for $M = 30M_\odot$, so it is suitable to reduce the Fe yields by a factor of 2[16,1].

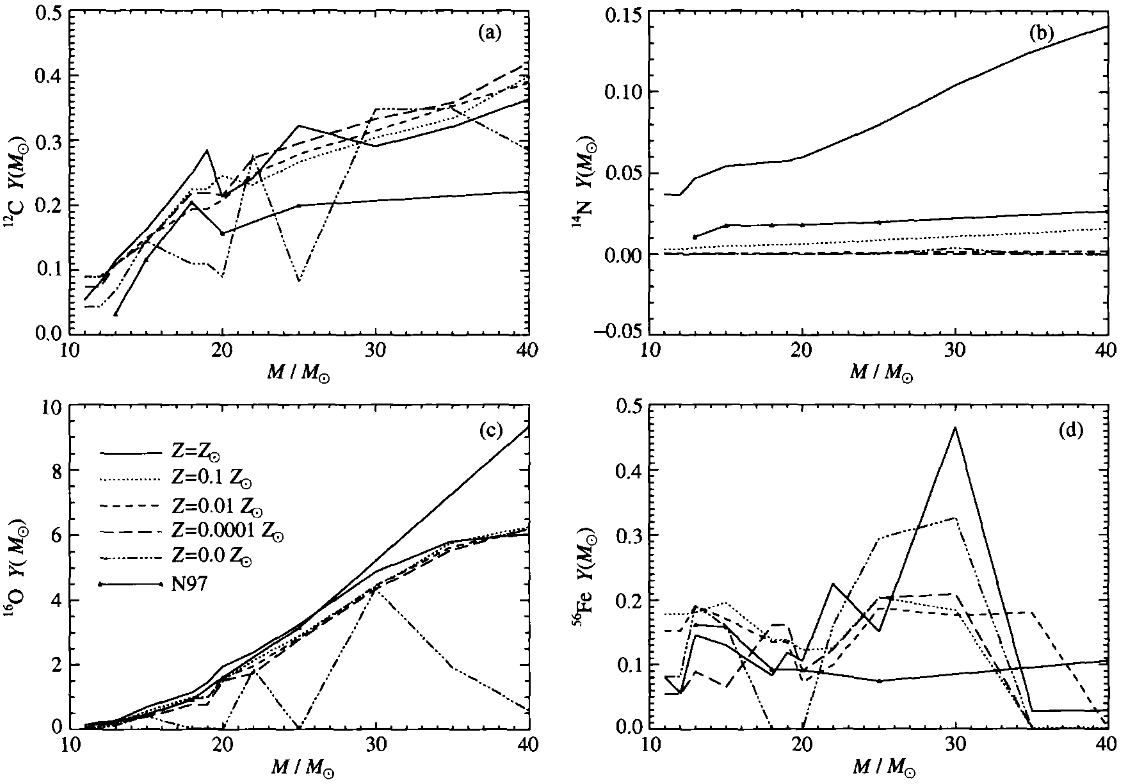

Fig. 2. Yields of ^{12}C, ^{14}N, ^{16}O and ^{56}Fe isotopes of SN Ⅱ explosion[6,8].

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[1] Liang, Y. C. et al. Sources of carbon and the evolution of the abundance of CNO elements with different stellar nucleosynthesis yields. A&A (in press).

2.2 Massive stars with stellar wind mass loss

Some authors considered the wind mass loss during the stellar evolution, especially for Wolf-Rayet (W-R) stage of the massive stars. In general, stars with initial mass $M > 40M_\odot$ can evolve through W-R stage[17]. Statistics showed that stars with $M > 30M_\odot$ can evolve through W-R stages in Large Magellanic Cloud, the mass limit is about $50M_\odot$ in Small Magellanic Cloud, and the value is about $35M_\odot$ in the solar vicinity. W-R stars are easily detectable due to their intrinsic brightness and the profound effects on the interstellar environment. Both Refs. [7] and [10] considered radiative-driven stellar wind in calculation of the evolution and nucleosynthesis of massive stars. The synthesized C, N, O elements, C in particular, are ejected into ISM during stellar wind mass loss. The main parameters adopted by Refs. [7] and [10] are presented in Table 3, where H_P is the local pressure scale height. Padova group has precisely calculated the stellar evolution of $0.6M_\odot < M < 120M_\odot$ stars with different metallicities[10]. Core overshoot is $0.25H_P$ for stars with $1.0M_\odot < M < 1.5M_\odot$, and $0.5H_P$ for stars with above. For the envelope overshoot, they adopted $0.7H_P$ for all the mass range considered.

Table 3 Main parameters of stellar evolution and nucleosynthesis[7,10]

	Ref. [7]	Ref. [10]
Initial mass	$1 \sim 120M_\odot$	$9 \sim 120M_\odot$
Metallicities	$(Z, Y) = (0.001, 0.243)$, $(0.020, 0.300)$	$Z = 0.0004$, 0.004, 0.008, 0.02, 0.05
Wind mass loss rate	$\dot{M} \sim M^{2.5}$ $\dot{M} \sim Z^{0.5}$	$\dot{M} \sim M^{2.5}$ $\dot{M} \sim Z^{0.5}$
$^{12}C(\alpha, \gamma)^{16}O$ rate	See Ref. [15]	See Ref. [14]
Radiative opacities	See Ref. [18]	See Ref. [19]
Neutrino loss	See Ref. [20]	See Ref. [21]
Overshooting	Moderate: $0.20H_P$	See text

Fig. 3 displays the wind and total net yields of massive stars from Ref. [7] (w refers to wind and t refers to total). Fig. 4 shows the corresponding yields in Ref. [10], where the contributions of stellar wind (w) are net yields; total yields (t). Figs. 3 and 4 show that metallicities sufficiently influence the C yields of W-R stars. The C contribution from stellar wind of stars with $Z = 0.02$ is clearly higher than those of the stars with $Z = 0.001$. For massive stars, metallicity generally influences their evolution through

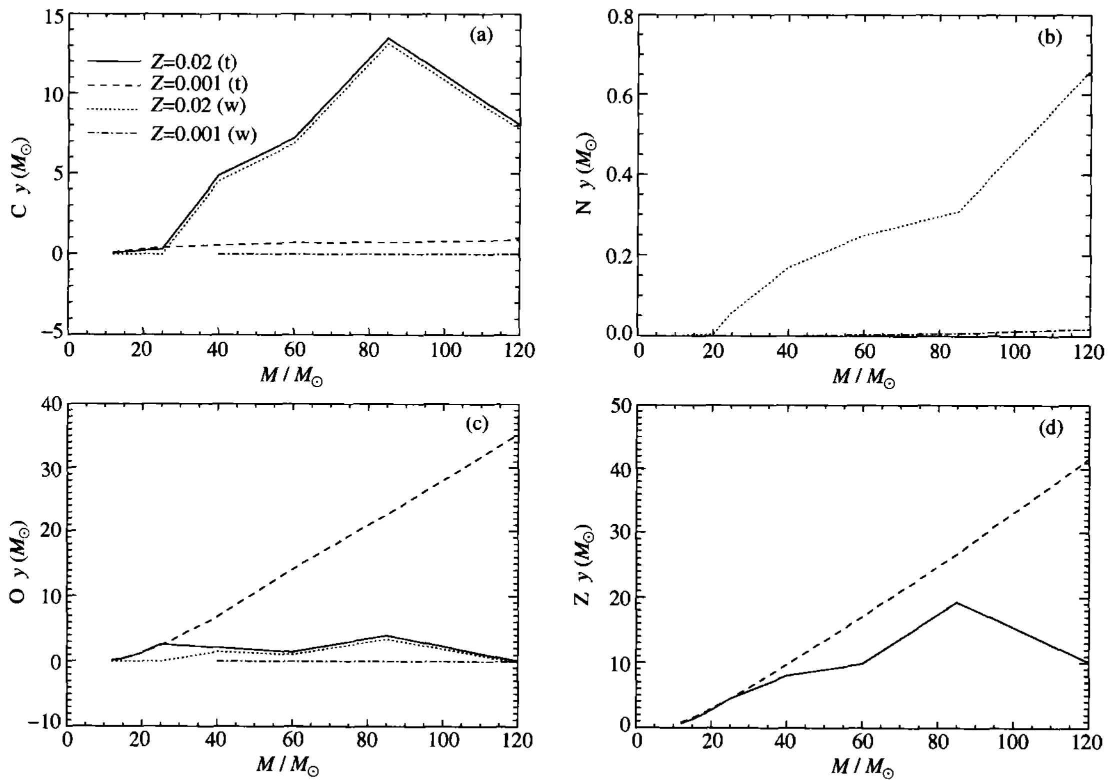

Fig. 3. Stellar wind and total yields of massive stars from Ref. [7].

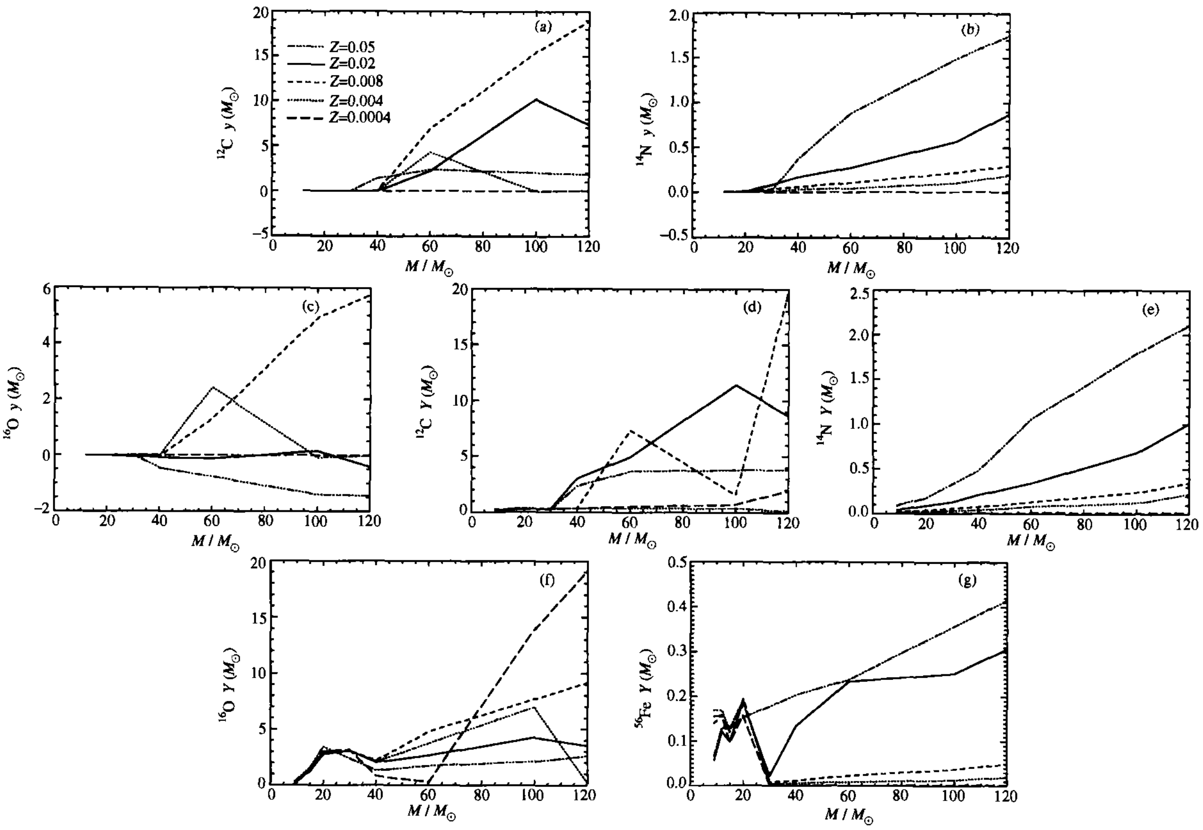

Fig. 4. Stellar wind and total yields given in Ref. [10]. (a), (b) and (c) for "w"; (d), (e), (f) and (g) for "t".

bound-free and line opacities, which are important in the very outer layers. In this way, metallicity influences the outer opacities and then the mass loss rates by stellar wind in massive stars[7,10]. However, the C yields of stars with higher metallicity, such as $Z = 0.05$, decrease again, since a higher mass loss rate is able to take more helium away before it turned to carbon, and with an increasing metallicity an increasing fraction of the original carbon is turned to ^{14}N in the CNO circle[10]. Thus, N yields increase with the increases of mass and metallicity. However, Ref. [7] only gives N yields of stellar wind but leares the total N yields, and Fe yields untouched. Fe element is only produced through SN Ⅱ explosion, and more Fe element is produced by the higher metallicity stars. O element is produced mainly by SN Ⅱ explosion. In general, the higher the mass is, the higher the O yield will be. Comparing the results of Refs. [7] and [10], we find that Ref. [7] gives the higher C yields though the higher $^{12}\mathrm{C}(\alpha, \gamma)^{16}\mathrm{O}$ rate is adopted, which means that the stellar wind mass loss of massive stars will influence the nucleosynthesis of C element strongly.

For a massive star, mass loss is a very important process, which affects the evolution and nucleosynthesis of the star. Many investigators adopted the yields given by Ref. [7] in their GCE models, and predicted very significant results, especially for the sources of carbon. The yields given by Ref. [10] have been used in GCE models widely; however, the corresponding yields of LIMS should be chosen from the similar nucleosynthesis conditions, as in Refs. [2~4].

3 Binary stars through type Ia supernova explosion

There are spectroscopic and photometric indications that SN Ia explosion originates from white dwarfs that are composed of C—O core with strongly degenerate electrons and have accreted sufficient mass from a companion to trigger an explosion. When the mass of the white dwarf becomes larger than a critical value due to accreting ejecta from the companion, fuel ignition under highly degenerate conditions causes the explosion[22]. In nucleosynthesis calculation, the mass of companion star of the accreting white dwarf (or the accretion rate that determines the carbon ignition density) is one of the major uncertainties involved in SN Ia explosion. Another major uncertainty is the flame speed after ignition. Considering these uncertainties, Nomoto's group[9] calculated some sets of nucleosynthesis yields, with the models C6, C8, W6, W7, W70, W8, WDD1, WDD2 and WDD3, among which the results of W7 model are used widely in GCE calculations[16]. The main product of SN Ia explosion is Fe element, with an amount of $0.613M_{\odot}$[9]. Generally, the maximum main sequence mass of the binary system leading to SN Ia explosion is $16M_{\odot}$ (or $12M_{\odot}$ with strong overshooting considered), and the corresponding minimum mass is $3M_{\odot}$[16]. SN Ia produces heavy elements on a long time scale in the late phase of the galactic evolution since the long lifetime of the progenitor.

In summary, stellar nucleosynthesis yield is a vital parameter in GCE model, and different yields can provide different GCE scenarios. For yields of LIMS, the new results[2~5] are used in GCE calculations at present rather than the old results in Ref. [1] which can not fit some observations[23]. In addtion, it is suitable to choose the results of Refs. [2]~[4] to be yields of LIMS and those of Ref. [10] for massive stars because they adopted similar parameters (Padova group). Moreover, Ref. [4] gives the yields of the stars with lower metallicity, which is $Z=0.004$, and it is important for exploring the contributions of AGB stars to elements in the early stage of our galaxy. The metallicity-dependent yields of massive stars given by Ref. [6] are important for studying the evolution of elements. In particular, the yields of zero metallicity stars are of significante for studying the first generation stars. The authors of Refs. [7] and [10] considered the stellar wind mass loss of massive stars in nucleosynthesis calculations, which is very important to Wolf-Rayet stars, hence to carbon.

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References

1 Renzini, A. et al. Advanced evolutionary stages of intermediate-mass stars Ⅰ: Evolution of surface compositions. A&A, 1981, 94: 175.

2 Marigo, P. et al. The TP-AGB phase: a new model. A&A, 1996, 313: 545.

3 Marigo, P. et al. TP-AGB stars with envelope burning. A&A, 1998, 331: 564.

4 Marigo, P. Chemical yields from low- and intermediate-mass stars: model predictions and basic observational constraints. A&A, 2001, 170: 194.

5 van den Hoek, L. B. et al. New theoretical yields of intermediate mass stars. A&AS, 1997, 123: 305.

6 Woosley, S. E. et al. The evolution and explosion of massive stars Ⅱ. Explosive hydrodynamics and nucleosynthesis. ApJS, 1995, 101: 181.

7 Maeder, A. Stellar yields as a function of initial metallicity and mass limit for black hole formation. A&A, 1992, 264: 105.

8 Nomoto, K. et al. Nucleosynthesis in type Ⅱ supernovae. Nucl. Phys., 1997, A616: 79c.

9 Nomoto, K. et al. Nucleosynthesis in type Ia supernovae. Nucl. Phys., 1997, A621: 467c.

10 Portinari, L. et al. Galactic chemical enrichment with new metallicity dependent stellar yields. A&A, 1998, 334: 505.

11 Groenewegen, M. A. T. et al. Synthetic AGB evolution Ⅰ: A new model. A&A, 1993, 267: 410.

12 Reimers, D. In Baschek B, et al. (eds.) Problems in Stellar Atmospheres and Envelopes. New York: Springer-Verlag, 1975, 229.

13 Vassiliadis, E. et al. Evolution of low- and intermediate-mass stars to the end of the asymptotic giant branch with mass loss. ApJ, 1993, 413: 641.

14 Caughlan, G. R. et al. Thermonuclear reaction rates V. At. Data and Nucl. Data Tables, 1988, 40: 283.

15 Caughlan, G. R. et al. Tables of thermonuclear reaction rates for low-mass nuclei ($1\leqslant Z\leqslant 14$). At. Data and Nucl. Data Tables, 1985, 32: 197.

16 Timmes, F. X. et al. Galactic chemical evolution: hydrogen through zinc. ApJS, 1995, 98: 617.

17 Maeder, A. et al. Massive star populations in nearby galaxies. ARA&A, 1994, 32: 227.

18 Rogers, F. J. et al. Radiative atomic Rosseland mean opacity tables. ApJS, 1992, 79: 507.

19 Iglesias, C. A. et al. Spin-orbit interaction effects on the Rosseland mean opacity. ApJ, 1997, 397: 717.

20 Itoh, N. et al. Neutrino energy loss in stellar interiors Ⅲ: Pair, photo, plasma, and bremsstrahlung processes. ApJ, 1989, 339: 354.

21 Munakata, H. et al. Neutrino energy loss in stellar interiors. ApJ, 1985, 296: 197.

22 Whelan, J. et al. Binaries and supernovae of type I. ApJ, 1973, 186: 1007.

23 Gustafsson, B. et al. The origin of carbon, investigated by spectral analysis of solar-type stars in the Galactic disk. A&A, 1999, 342: 426.