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Yields of Nucleosynthesis from Massive and Intermediate Mass Stars and Constraints on their Final Evolution

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Abstract. Nucleosynthetic yields and production rates of helium and heavy elements are derived using new initial mass functions which take into account the recent revisions in O star counts and the stellar models of Maeder (1981a, b) which incorporate the effects of massloss on evolution. The current production rates are significantly higher than the earlier results due to Chiosi & Caimmi (1979) and Chiosi (1979), and a near-uniform birthrate operating over the history of the galactic disc explains the currently observed abundances. However, the yields are incompatibly high, and to obtain agreement it is necessary to assume that stars above a certain mass do not explode but proceed to total collapse. Further confirmation of this idea comes from the consideration of the specific yields and production rates of oxygen, carbon and iron and the constraints imposed by the observational enrichment history in the disc as discussed by Twarog & Wheeler (1982). Substantial amounts of ^{4}He and ^{12}C, amongst the primary synthesis species, are contributed by the intermediate mass stars in their wind phases. If substantial numbers of them exploded as Type I SN, their contribution to the yields of ^{12}C and ^{56}Fe would be far in excess of the requirements of galactic nucleosynthesis. Either efficient massloss precludes such catastrophic ends for these stars, or the current stellar models are sufficiently in error to leave room for substantial revisions in the specific yields. The proposed upward revision of the $^{12}C\,(\alpha, \gamma)^{16}O$ rate may produce the necessary changes in stellar yields to provide a solution to this problem. Stars that produce most of the metals in the Galaxy are the same ones that contribute most to the observed supernova rate.

Key words: stars, nucleosynthesis—stars, birthrate—stars, intermediate mass—supernovae, Type I

1. Introduction

Our understanding of the chemical enrichment of the interstellar medium is critically dependent upon our knowledge of the processes of nucleosynthesis, mass ejection and final evolution of stars. Recent evolutionary computations of massive as well as low and intermediate mass stars include the effects of massloss via stellar winds and contain the details of nucleosynthetic yields as a function of the initial stellar mass. Along with the theoretical developments, new and vastly improved observational data have become available, and a meaningful comparison of theoretical results with what is actually observed is now possible. Such comparisons are crucial in limiting theoretical possibilities, and they provide important constraints for the models of chemical evolution of galaxies.

In an earlier paper (Mallik 1981), we had investigated the rate of element production in the solar neighbourhood using the stellar nucleosynthesis data from Arnett (1978, hereinafter A78) and the birthrate function determined by Lequeux (1979). The essential new feature of Lequeux's birthrate function was a correction applied to the O star counts based on the belief that a significant fraction of them belonged to an older, evolved population. When the observed surface densities were corrected for the presence of this population, the numbers dropped considerably for masses above $24\,M_{\odot}$. The derived birthrate function was fairly steep (with a slope of -2.1, compared to the Salpeter function with its slope of -1.35). As a result, the current element production rate turned out to be rather low. If the observed abundances in the disc were assumed to be a result of nucleosynthesis in massive stars, the past star formation rate had to be much higher. The inferred high star formation rate in the past would violate the continuity constraint on the initial mass function (Tinsley 1977a; Miller & Scalo 1979, hereinafter MS).

It is now fairly certain that Lequeux had overcorrected for the OB 'runaway' stars and, if at all, one should use the surface densities obtained by him with the 'runaways'. Moreover, Lequeux possibly underestimated the effects of interstellar extinction and arrived at rather low surface densities (see Garmany, Conti & Chiosi 1982). For both these reasons the birthrate function determined by Lequeux is deemed unreliable. There have been important revisions to the IMF for the massive stars, correcting for the earlier incompleteness of the data, and using better evolutionary models that take into account the effects of massloss. They imply a higher birthrate for the massive stars and therefore, a higher current rate of nucleosynthesis, and hence a slower variation of the stellar birthrate during the lifetime of the galactic disc. From an observational study of the ages and metallicity distribution of F and G dwarfs, Twarog (1980) concluded that the stellar birthrate had been more or less uniform.

A related problem in the chemical evolution of galaxies is the ratio of helium to heavy element enrichment. From a theoretical point of view, a linear correlation is expected. Peimbert (1977), Lequeux *et al.* (1979) and Rayo, Peimbert & Torres-Peimbert (1982) find a steep linear correlation with $\Delta Y/\Delta Z \sim 2.0$–$3.0$. Shaver *et al.* (1983) conclude, from a study of radio recombination lines in galactic H II regions that $\Delta Y/\Delta Z$ is close to 0.8, a value much smaller than those quoted by Peimbert and coworkers. The steep slope of helium to heavy-element enrichment, if confirmed, would pose a serious theoretical problem, since no combination of any reasonable IMF and the available stellar nucleosynthesis data is able to produce this slope (Hacyan *et al.* 1976; Gingold 1977; Mallik 1980). Chiosi and coworkers (Chiosi & Caimmi 1979; Chiosi 1979) argued that if massloss from massive stars were taken into account in the evolutionary models, the mass of the helium core M_{α}, for a given initial mass M of the star, would be greatly reduced and subsequent evolution of the core would, then, generate heavier elements in much smaller quantities. Using A78 but a modified M (M_{α}) relation, they computed a much higher $\Delta Y/\Delta Z$. They further noted that this was a lower limit since the loss of He-rich material by stellar wind, during the core H- and He-burning phases, was not taken into account. However, the reduced ability of massive stars to produce heavy elements was reflected in a derived low rate of nucleosynthesis. The past star formation rate was inferred to be higher by a factor of 25–30.

New evolutionary models have since been computed by Maeder (1981a, b) who includes the effects of massloss and follows the evolution beyond He-burning to core carbon ignition. Maeder has studied the $M(M_\alpha)$ relation implied by his models and finds that it is more in agreement with the one used in A78. Maeder (1981b) computed the stellar yields of helium and heavy elements as a function of the stellar mass from his models and used the same to calculate nucleosynthetic yields from a generation of stars. Using MS and the new stellar data, he found that a maximum variation of a factor of 3 in the SFR over the history of the disc is sufficient to explain the observed abundances. This result is in near perfect agreement with the earlier estimate by Wheeler, Miller & Scalo (1980, hereinafter WMS). Maeder (1981b) obtained a $\Delta Y/\Delta Z \sim 0.75$ which is similar to the previous estimates, when no massloss was taken into account, and concluded that massloss in massive stars does not alter this ratio significantly. None of these authors took into account the contribution of the intermediate mass stars although these stars are known to produce significant amounts of He and CN elements (Renzini & Voli 1981), and may also contribute to Fe enrichment should they explode finally as Type I SN (Iben 1981).

The rate of nucleosynthesis depends on the current SFR and the upper portion of the initial mass function. The yield is independent of the former and depends on the complete mass range of the IMF since, by definition, it is the ratio of the mass of a certain species newly formed and ejected by a generation of stars to the mass of that generation that remains locked up in unevolved stars and stellar remnants. The ratio $\Delta Y/\Delta Z$, on the other hand, depends only on the IMF of the evolving stars and most critically on its slope, since it determines the relative numbers of helium and heavy-element producing stars. Twarog & Wheeler (1982, hereinafter TW) have compared the data obtained by Twarog (1980) and Clegg, Lambert & Tomkin (1981) with model predictions based on the production rates of WMS and the assumption of a uniform SFR. They discovered that the Fe production rate had to be reduced to match the age-metallicity relation of Twarog. Secondly, even when the Fe yield was fixed at the value dictated by the observations, the enrichment history of other elements could be faithfully reproduced if the integrated yields of these elements relative to Fe were reduced by fixed amounts compared to the WMS values. This led TW to investigate into the possible alterations of the IMF that would result in reduced yields and reduced element production rates without jeopardizing the constraint on the variation of SFR. They concluded that observations could be reconciled with the theory, if the IMF were cut off at some upper limit so that stars that are more massive do not explode at all. For example, on the assumption that oxygen came entirely from massive stars, they found that a cut-off at 25 $M_\odot$ was required by the observations for a slope of the IMF similar to the MS value of -2.3, and in this case both Fe and C were underproduced in massive stars. They suggested that these deficiencies could be made up by contributions from intermediate mass stars (IMS, $2.5 < M/M_\odot \lesssim 9$) although this possibility was not explored in detail by these authors. They, however, put rather stringent limits on the production of C and Fe from IMS.

In the present paper, we address ourselves to many of the questions regarding stellar nucleosynthesis and chemical evolution of the disc. The recent modifications of the O star counts have been taken into account to derive new consolidated IMFs. The current SFR is then fixed on the basis of the continuity constraint. These IMFs have been used in conjunction with the stellar models of Maeder to estimate the nucleosynthetic yields from massive stars, the current rate of nucleosynthesis and $\Delta Y/\Delta Z$. Nucleosynthesis by the intermediate mass stars has also been calculated from the models of Renzini & Voli (1981). The net production rates and yields are compared with observations to infer the variation of SFR and place constraints on nucleosynthesis from massive stars.

To study the nucleosynthesis pattern of the individual species further, the stellar data from A78 have been used. The limits imposed by the galactic abundance data on the production of the major nucleosynthesis species ^{12}C, ^{16}O and ^{56}Fe require upper mass cut-offs to the IMF. The effect of such a procedure on the yields and the helium to heavy-element ratio has been investigated in some detail. On the assumption that ^{16}O is produced almost exclusively by massive stars, our calculations indicate that substantial amounts of ^{12}C and small amounts of ^{56}Fe are required to be produced by other sources which brings into focus the role of the intermediate mass stars in galactic nucleosynthesis. These stars produce and eject varying amounts of ^{4}He, ^{12}C, ^{13}C, ^{14}N and *s*-process elements during their quasi-static evolution. If the IMS end their lives as white dwarfs after ejecting their residual envelopes as planetary nebulae, they add little to the production of other primary species. However, the possibility of a more catastrophic end, where some of these stars explode as carbon detonation or deflagration supernovae, has been extensively discussed in the literature (Arnett 1969; Tinsley 1977b, 1980a; Wheeler 1978, 1981; Nomoto 1981, 1984). In such an event, copious amounts of ^{56}Fe, other iron-peak elements, some intermediate mass elements (^{40}Ca, ^{28}Si, ^{32}S *etc.*) as well as ^{12}C and ^{16}O may be produced from the disrupted cores of these stars. The occurrence of such an eventuality is principally controlled by the quiescent massloss phenomenon during the red giant phases of evolution of these stars and may be prevented altogether in case of efficient massloss. In Section 3 of this paper we calculate the magnitude of enrichment due to this process and discuss the rather drastic effects this should have on the observed abundances.

2. Nucleosynthetic yields, current production rate of metals and the ratio of helium to heavy element enrichment

2.1 *Initial Mass Function and the Current Star Formation Rate*

The essential first step in determining the IMF is to obtain from counts of stars reliable surface densities of main sequence stars as a function of their mass, the so-called present day mass function (PDMF). Since massive stars are fewer in number, the errors in the derived PDMF are rather large. The poor luminosity designation of O stars posed a further problem in the earlier determinations. It has also been known for some time that the hydrogen-burning main-sequence for massive stars is much wider than previously assumed, and B type supergiants should also be included in the derivation of the PDMF. Owing to these drawbacks the PDMFs of Miller & Scalo (MS) and Lequeux (1979) are increasingly unreliable at larger masses. Improvements in O star catalogues with large data sets and proper luminosity identification of these stars have corrected for these deficiencies. Using larger volume-limited samples of OB stars, several authors, in the last couple of years, have rederived the PDMFs for massive stars in the Galaxy (Garmany, Conti & Chiosi 1982; Bisiacchi, Firmani & Sarmiento 1983). The surface densities in the different mass intervals are considerably larger than the corresponding values in MS and the PDMFs extend to higher masses. Fig. 1 displays the PDMFs determined by the different authors. The uncertainties in the numbers are much less than the differences produced by the new data on O stars. The most recent determination is due to Humphreys & McElroy (1984). Their derived IMFs are very similar to that of Bisiacchi *et al.* In our calculations the data from Garmany *et al.* and Bisiacchi *et al.* have been used.

While the IMF is generally assumed to be independent of time, the time variation of SFR is explicitly considered, since the presently observed number of main-sequence stars at any mass contains stars of this mass formed at different times but within one main-sequence lifetime of the present corresponding to this mass. For the massive stars, which are shortlived compared to the age of the Galaxy, the PDMF divided by the main-sequence lifetime yields directly the current birthrate. For stars with long lifetimes, the history of the birthrate appears in the relation between PDMF and IMF (see Tinsley 1980a, for details). MS has emphasized that a choice of an IMF with an arbitrary choice of SFR will not, in general, reproduce the PDMF and a consistent choice has to be always made in this regard. Further, the continuity of the IMF near the present turn-off mass of the Galaxy provides a fundamental constraint on the variation of SFR with time. We follow the procedure laid down in MS and derive consolidated new IMFs using the counts from MS for stars less than 20 $M_{\odot}$, and the new counts from Garmany *et al.* and Bisiacchi *et al.* for stars more massive than 20 $M_{\odot}$. The quantity finally obtained, after satisfying the continuity constraint for a time-varying birthrate, is $\xi(\log m)$ which is defined as the total number of field stars that have ever

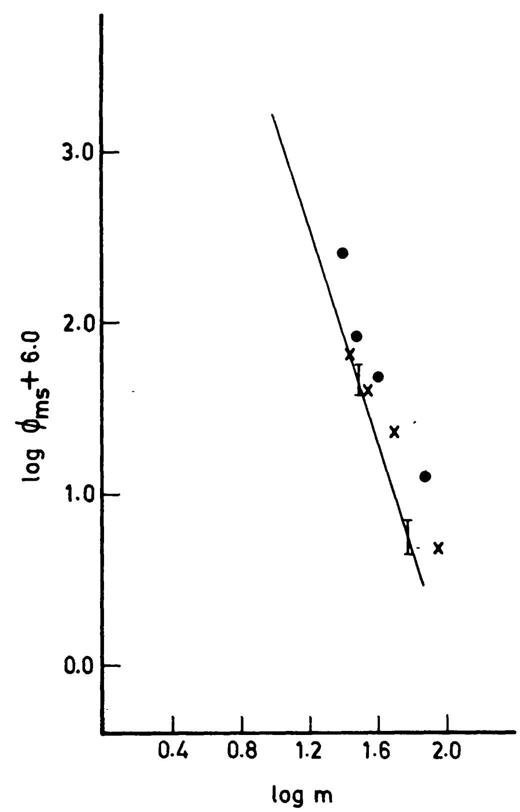

Figure 1. The present day mass functions (PDMF) from MS (solid line), Garmany *et al.* (crosses) and Bisiacchi *et al.* (filled circles).

formed per pc^2 per $\log m$ in the solar neighbourhood. This is related to the normalized field star IMF $\phi(m)$ through

$$m\phi(m)\psi_1 = \log e \frac{\xi(\log m) b(T_0)}{T_0}. \quad (1)$$

Here ψ_1 is the current SFR, T_0 the age of the Galaxy and $b(T_0)$ the birthrate at T_0 in units of the average birthrate. All through the paper m will denote the initial main-sequence mass in solar units. If SFR decreased with time, for an assumed T_0 of 12×10^9 yr, the extreme present birthrate satisfying the continuity constraint (MD birthrate in MS parlance) is given by $b(T_0) = 0.24$. For a uniform birthrate $b(T_0) = 1$. We have integrated Equation (1) to obtain ψ_1 for the prescription of a uniform birthrate and a maximum allowable decreasing birthrate. Simple power-law fits to these IMFs and the derived values of ψ_1 are summarized in Table 1. It is seen that ψ_1 is relatively insensitive to the changes at the upper end of the IMF brought about by the new counts on O stars. The $\phi(m)$'s for the uniform birthrate are somewhat different from the $\phi(m)$'s for the MD birthrate. We emphasize that the use of an arbitrary ψ_1 with any $\phi(m)$ will, in general, lead to erroneous results.

2.2 *Production Rates and Nucleosynthetic Yields from Massive Stars*

Once $\phi(m)$ and ψ_1 are known, it is straightforward to obtain the current production rates of elements and the nucleosynthetic yields. Arnett (A78) computed the absolute yields of abundant nuclei as a function of the helium core mass, M_α, which was related to the initial main-sequence mass M of the star through a $M(M_\alpha)$ transformation based on conservative evolutionary sequences. Since then, Maeder (1981a, b) has evolved models with massloss and obtained stellar yields as a function of the stellar mass. An important feature of the mass-losing models is the evaluation of the separate contributions to the enrichment from the stellar wind and the final supernova event. The stellar wind contribution is important during the longer-lived H- and He-burning phases and for helium and some of the CNO elements. Maeder's models thus provide an opportunity to study in greater detail the production of helium and also the ratio of helium to heavy-element enrichment. We have used Maeder's models to compute the

Table 1. The initial mass function and the current star formation rate.

Data	Birthrate prescription	$\phi(m)$	Current SFR ψ_1 $M_\odot\,pc^{-2}\,Gyr^{-1}$	Reference in text
MS for $m < 20$, and Garmany *et al.* for $m > 20$	Maximum, decreasing	$0.40m^{-2.82}$, $m < 10$ $0.10m^{-2.21}$, $m \geqslant 10$	3.0	1(a)
	Uniform	$0.42m^{-2.68}$	4.6	1(b)
MS for $m < 20$, and Bisiacchi *et al.* for $m > 20$	Maximum, decreasing	$0.38m^{-2.6}$	3.0	1(c)
	Uniform	$0.50m^{-2.69}$, $m < 10$ $1.00m^{-3.01}$, $m \geqslant 10$	4.6	1(d)

nucleosynthetic yields and the current production rates. We have considered his case B results only. In Maeder's work the stellar yields are given by mp_{Ym} and mp_{Zm} which are the respective masses of newly synthesized helium and metals ejected into the interstellar medium from a star of initial mass m. Both p_{Ym} and p_{Zm} are the sums of the contributions from the stellar wind (p_{im}^{wind}) and the supernova event (p_{im}^{SN}). While p_{Ym}^{wind} is substantial for all masses, Maeder's work shows that p_{Zm}^{wind} is important only for certain special cases when Wolf-Rayet stars of the type WC may form.

The production rate of newly synthesized metals at time t is then

$$\int_{m_t}^{\infty} mp_{Zm}\phi(m)\psi(t-\tau_m)\mathrm{d}m \tag{2}$$

where $\psi(t)$ is the SFR, τ_m the lifetime of the star of mass m and m_t the turn-off mass. To evaluate the current production rate, t is replaced by the age of the Galaxy and m_t by m_1, the present turn-off mass. Since most of the synthesis is effected by rather massive stars for which $\tau_m \ll T_0$, expression (2) is simplified further by the use of the instantaneous recycling approximation to

$$\dot{\Sigma}_Z = \psi_1 \int_{m_1}^{\infty} mp_{Zm}\phi(m)\mathrm{d}m \tag{3}$$

where ψ_1 is the current SFR. If a star of mass m leaves a remnant of mass r_m, the fractional mass returned to the interstellar medium per generation is given by

$$R = \int_{m_1}^{\infty} (m-r_m)\phi(m)\mathrm{d}m. \tag{4}$$

Therefore, the heavy element yield

$$y_Z = \frac{1}{1-R}\int_{m_1}^{\infty} mp_{Zm}\phi(m)\mathrm{d}m. \tag{5}$$

Similarly, for helium

$$\dot{\Sigma}_Y = \psi_1 \int_{m_1}^{\infty} mp_{Ym}\phi(m)\mathrm{d}m \tag{6}$$

and

$$y_Y = \frac{1}{1-R}\int_{m_1}^{\infty} mp_{Ym}\phi(m)\mathrm{d}m.$$

For evaluating R, we have used the prescription of Iben & Truran (1978) for the mass of the white dwarf as a function of the initial main-sequence mass and have assumed $r_m = 1.4$ for $m > 8$.

The results are presented in Table 2a. The rate of nucleosynthesis is estimated to be much higher than the earlier estimates (Chiosi & Caimmi 1979; Chiosi 1979; Mallik 1981). The earlier low values are attributable to the use of a wrong IMF in the case of Mallik (1981) and to the use of a wrong $M(M_\alpha)$ transformation in the case of Chiosi & Caimmi (1979) and Chiosi (1979). Thus, massloss in massive stars does not seem to produce any major effect on the final rate of nucleosynthesis. The rate is a bit higher than the WMS rate partly due to the use of a different IMF and partly due to different stellar yields. The ratio of helium to heavy-element enrichment is uniformly low and, contrary to the assertion of Chiosi and Caimmi, we conclude that massloss has little effect on this ratio even though the wind contribution to He-enrichment has been explicitly taken into account here.

2.3 *Contribution of Intermediate Mass Stars*

Although massive stars are generally held responsible for element synthesis, the intermediate mass stars make significant contribution to the enrichment of ^{4}He, ^{12}C, ^{14}N, ^{13}C and *s*-process elements. We have used the stellar yields from Renzini & Voli (1981) to estimate the enrichment rate of helium and CNO elements. The dredge-up and mixing of enriched material into the envelopes of these stars and hence the final enrichment of the interstellar medium are sensitively dependent on the massloss parameter η, and the ratio of the mixing length to the pressure scale height, denoted by the parameter α. Higher rates of massloss reduce the time spent by these stars on the asymptotic-giant branch and therefore the growth of the core is also reduced and the total amount of matter dredged up is less. In the absence of any massloss, enormous amounts of ^{12}C and *s*-process elements would be produced by these stars, far in excess of the requirements of galactic nucleosynthesis (Iben 1981). The effect of the parameter α is to induce burning at the base of the convective envelope which causes further processing of the material dredged up following each He-shell flash episode. The consequence of this is to produce fresh ^{14}N and ^{13}C in CNO cycle at the expense of ^{12}C and ^{16}O which were produced in He-burning. Some amounts of ^{4}He are also produced in this case. To have representative estimates of the enrichment caused by intermediate mass stars we have chosen three of the cases considered by Renzini & Voli: Case a, with $\eta = \frac{1}{3}$, $\alpha = 0$, case e with $\eta = \frac{1}{3}$, $\alpha = 2$, and case f with $\eta = \frac{2}{3}$, $\alpha = 0$. In Table 2b, the results are given. It is obvious that intermediate mass stars are an important source of ^{4}He and they add to the metals mostly in the form of CNO elements. The approximation of instantaneous recycling used here for the IMS is still justified because the bulk of the contribution comes from $m > 3.0$ with peaks around $m = 5$ or 6, and the main-sequence lifetime of a 3 $M_\odot$ star is only 0.3 Gyr.

Table 2a. Production rates and yields from massive stars.

IMF	R	$\dot{\Sigma}_Y$ ($M_\odot$ pc^{-2} yr^{-1})	$\dot{\Sigma}_Z$ ($M_\odot$ pc^{-2} yr^{-1})	y_Y	y_Z	$\Delta Y/\Delta Z$
1(a)	0.352	3.90(−11)	5.86(−11)	0.020	0.030	0.48
1(c)	0.389	4.08(−11)	5.61(−11)	0.022	0.031	0.51

Table 2b. Contribution from intermediate-mass stars.

IMF	η	α	$\dot{\Sigma}_Y$ ($M_\odot$ pc^{-2} yr^{-1})	$\dot{\Sigma}_{CNO}$ ($M_\odot$ pc^{-2} yr^{-1})
	1/3	0	1.30(−11)	4.62(−12)
1(a)		2	1.51(−11)	8.72(−12)
	2/3	0	1.08(−11)	3.18(−12)
	1/3	0	1.84(−11)	6.33(−12)
1(c)		2	2.14(−11)	8.86(−12)
	2/3	0	1.53(−11)	4.44(−12)

The total production rates are the sums of the contributions from massive stars and intermediate mass stars. These along with the yields are given in Table 3. The proportionate increase in helium production due to the contribution of intermediate-mass stars is larger. These yields imply $\Delta Y/\Delta Z = 0.58$–0.69, for an initial $Y = 0.28$. The ratio is somewhat increased over the values obtained when only massive stars were considered (*vide* Table 2a). However, it is less than unity.

It should be noted that in the absence of massloss, the vast majority of these stars ($2 \lesssim m \lesssim 8$) would proceed to thermonuclear disintegration following carbon ignition in their degenerate cores. As the cores disrupt totally, large amounts of Fe-peak elements as well as carbon and oxygen should be added to the galactic pool. In our discussion so far, the rather drastic effects of core disruption have not been considered. For the massloss parameters used here, the maximum initial mass of a star becoming a white dwarf is either 4.75 ($\eta = \frac{1}{3}$) or 6.0 ($\eta = \frac{2}{3}$). Thus a crucial gap is left open, between 4.75 or 6.0, and 8.0 or 9.0 solar masses, for core disruption supernovae to occur. We postpone a discussion of this possibility to Section 3.

2.4 *The Yield*

The heavy element yields presented in column 6 of Table 2a and column 5 of Table 3 are rather high. Pagel & Patchett (1975) were the first to analyse in detail the abundance data in the solar neighbourhood and they arrived at a value of the yield between 0.004 and 0.006. Since then, several other studies have been made and somewhat higher values of yields have been obtained. Twarog (1980), in his study of the age-metallicity relation of the disc stars, determined the present value of $\Delta Z/y_Z$ to be 1.76, which, for a value of $\Delta Z = 0.02$ leads to a $y_Z = 0.0114$. Peimbert & Serrano (1982) have derived yields from observational data on a number of galaxies and in a variety of galactic objects. The range in the yields is rather narrow with all the values lying between 0.002 and 0.014. Their value for the solar neighbourhood is 0.007, almost a factor of two lower than Twarog's. Tinsley (1980b) has emphasized that all consistent models for the solar neighbourhood predict that the mean metallicity of disc stars lies within 20 per cent of the yield. Thus, assuming that the mean metallicity $\Delta Z = 0.8\ Z_\odot$, one obtains for the heavy element yield a range 0.013–0.019. All these values are lower than the computed yields based on the IMF we have advocated. From a detailed analysis of the data from Clegg, Lambert & Tomkin (1981) with the help of a standard infall model, Twarog & Wheeler (TW) came to the conclusion that the theoretical yields in WMS were too high.

Table 3. Total production rates and yields.

IMF	$\dot{\Sigma}_Y$ ($M_\odot$ pc^{-2} yr^{-1})	y_Y	$\dot{\Sigma}_Z$ ($M_\odot$ pc^{-2} yr^{-1})	y_Z
	5.20(−11)	2.68(−2)	6.32(−11)	3.25(−2)
1(a)	5.41(−11)	2.78(−2)	6.73(−11)	3.46(−2)
	4.98(−11)	2.56(−2)	6.18(−11)	3.18(−2)
	5.92(−11)	3.23(−2)	6.24(−11)	3.40(−2)
1(c)	6.22(−11)	3.39(−2)	6.50(−11)	3.55(−2)
	5.61(−11)	3.06(−2)	6.05(−11)	3.30(−2)

The IMFs used here are derived from higher stellar surface densities than those obtained in MS. Therefore, it is not surprising that the yields determined here are even higher. Unless the stellar yields are in error by large factors, there is no escape from the fact that the theoretical yields computed here are incompatible with observations.

2.5 *Effect of Cutoffs in the IMF*

As anticipated in the introduction, the nucleosynthetic yields per generation can be reduced without altering the IMF or the stellar yields if we assume that stars beyond a certain upper mass limit evolve to total collapse. This would help reduce the net contribution by massive stars to metal production.

The upper mass cutoffs in the IMF will also have the effect of reducing the current production rates. This leads to the following problem. A low current rate of nucleosynthesis implies that the past SFR was much higher to produce the currently observed abundances. However, other evidences (Twarog 1980) and the continuity constraint on the IMF require that the SFR is more or less uniform. The revised IMFs and Maeder's stellar yields used above, make the current production rate sufficiently high such that the need for a higher SFR in the past is precluded. With the introduction of the cutoffs in the IMF now, are we violating the constraint of uniform birthrate? In an effort to find an answer, we have introduced cutoffs to the IMF and recomputed $\dot{\Sigma}_Z$, $\dot{\Sigma}_Y$, y_Z, y_Y, R and derived $\langle\psi\rangle/\psi_1$ in each case. The results are displayed in Fig. 2, where m_u denotes the upper limit on the main-sequence mass beyond which stars are presumed to proceed to total collapse without adding to the enrichment of the ISM. As m_u increases, $\dot{\Sigma}_Z$ goes up and so does y_Z. $\langle\psi\rangle/\psi_1$ decreases. We find that there is a range in m_u for which y_Z lies in the range of observed values and $\langle\psi\rangle/\psi_1$ is within the limits consistent with a near uniform birthrate. With the IMF 1(a) a cutoff at $m_u = 48$ produces an yield $y_Z = 0.015$. The production rate of metals is 0.029 $M_\odot$ pc^{-2} Gyr^{-1} and $\langle\psi\rangle/\psi_1 = 2.7$. For $m_u = 39$, $y_z = 0.011$ and $\langle\psi\rangle/\psi_1 = 3.5$. This value is marginally consistent with a near uniform birthrate. Similar cutoffs are obtained for the IMF 1(c).

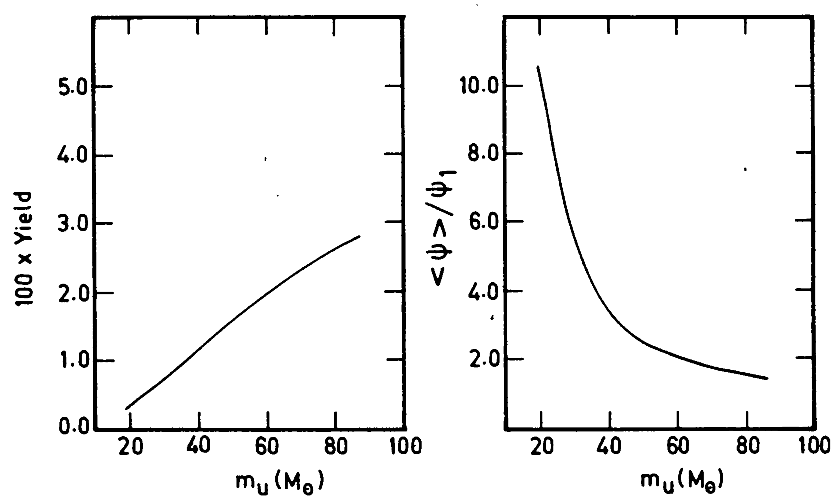

Figure 2. Yield and the variation of the star formation rate as a function of m_u. A value of $\Sigma = 50\ M_\odot$ pc^{-2} has been used.

A further effect of introducing the cutoffs in the IMF is to change the value of $\Delta Y/\Delta Z$. Since helium production is weighted heavily towards the lower masses, y_Y is, in general, less sensitive to the choice of m_u. Moreover, stars with $m > m_u$ evolve through the H- and He-burning phases before collapsing to black holes and p_{Ym}^{wind} is non zero for them. Thus y_Y/y_Z dramatically increases with decreasing m_u and $\Delta Y/\Delta Z$ is increased. For $m_u = 40$, $y_Y/y_Z = 1.76$ while for $m_u = 30$, it goes up to 2.47. We suggest that the large values of helium to heavy-element enrichment are an indirect indication of the massive stars evolving to black holes instead of producing supernovae and not an effect caused by internal adjustments in the star as a result of massloss (*cf.* Chiosi & Caimmi 1979).

3. The element enrichment pattern and the effect of carbon deflagration supernovae

In the previous section we discussed the metal production rate and heavy-element yield based on the stellar models of Maeder. Individual species were not considered. However, to gain a clearer understanding of the pattern of nucleosynthesis, it is more useful to consider the individual species. This is best done with the data from A78 where specific yields of He, C, O, Ne, Mg, Fe + Si as a function of the stellar mass are given. Observations as well as theory have suggested different enrichment histories for the primary elements like C, O and Fe (Clegg 1977; Tinsley 1979; Sneden, Lambert & Whitaker 1979). TW showed that a standard infall model with uniform birthrate was capable of reproducing this varied history of enrichment provided the yields were substantially reduced. Through this analysis they put limits on the contribution to element enrichment by IMS. The production of carbon in progenitors of planetary nebulae is a well-established fact. The important recent observation by Wu *et al.* (1983) of strong Fe II absorption lines in what is believed to be the stellar ejecta from SN 1006 and the earlier discovery by Kirshner & Oke (1975) of overabundance of iron in SN 1972e in NGC 5253 provide evidence of iron production in Type I supernovae which are believed to be the result of core disruption of relatively low-mass stars. We now investigate in some detail the contribution of IMS to galactic carbon production and the impact of Type I SN nucleosynthesis on the production of carbon, oxygen and iron.

3.1 *Constraints on Specific Production Rates*

Based on the abundance data of Clegg, Lambert & Tomkin (1981), and the age-metallicity relation of disc stars (Twarog 1980), Twarog & Wheeler were able to derive the net yield of iron and the ratio of the yields of carbon, neon, magnesium and iron to that of oxygen. The absolute production rates of oxygen, carbon and iron obtained by them are

$$\dot{\Sigma}_{\text{O}} = 1.44 \times 10^{-11}\, M_\odot\, \text{pc}^{-2}\, \text{yr}^{-1}, \qquad \dot{\Sigma}_{\text{C}} = 7.47 \times 10^{-12}\, M_\odot\, \text{pc}^{-2}\, \text{yr}^{-1},$$
$$\dot{\Sigma}_{\text{Fe}} = 3.92 \times 10^{-12}\, M_\odot\, \text{pc}^{-2}\, \text{yr}^{-1}. \tag{3.1}$$

The solar abundances of Cameron (1973) have been used in arriving at these numbers. These absolute rates have a 30–40 per cent uncertainty in them. In the following analysis, we shall accept as observed the values in (3.1). We further assume that the birthrate has been uniform during the evolutionary lifetime of the disc, and the IMFs we use accordingly are 1(b) and (d) from Table 1. The production rates of carbon, oxygen and iron as a function of m_u are displayed in Fig. 3. Here, m_u has the same significance as in Section 2. An examination of the figure reveals the following:

(i) For the IMF 1(b), at $m_u = 28$, the production rate of oxygen equals the net galactic production rate. The corresponding production rates of carbon and iron are respectively $6.26 \times 10^{-12}\ M_\odot\ \mathrm{pc}^{-2}\ \mathrm{yr}^{-1}$ and $3.96 \times 10^{-12} M_\odot\ \mathrm{pc}^{-2}\ \mathrm{yr}^{-1}$. Carbon is marginally underproduced in massive stars while the iron production rate seems adequate. Since A78 yields refer to Fe + Si and not Fe alone, it is possible that a part of the contribution here comes from unburned Si. Moreover, if a higher iron production rate of $4.9 \times 10^{-12}\ M_\odot\ \mathrm{pc}^{-2}\ \mathrm{yr}^{-1}$ were assumed (see Nomoto, Thielemann & Wheeler 1984), there is a predicted deficiency of 18 per cent in iron production from massive stars. On the assumption that oxygen is produced entirely in massive stars, the combination of our birthrate function and the stellar yield data from A78 precludes the participation of stars more massive than 28 $M_\odot$ in nucleosynthesis. At $m_u = 28$ the relative yields of carbon and iron are 0.43 and 0.28 respectively. The corresponding solar values are 0.42 and 0.22.

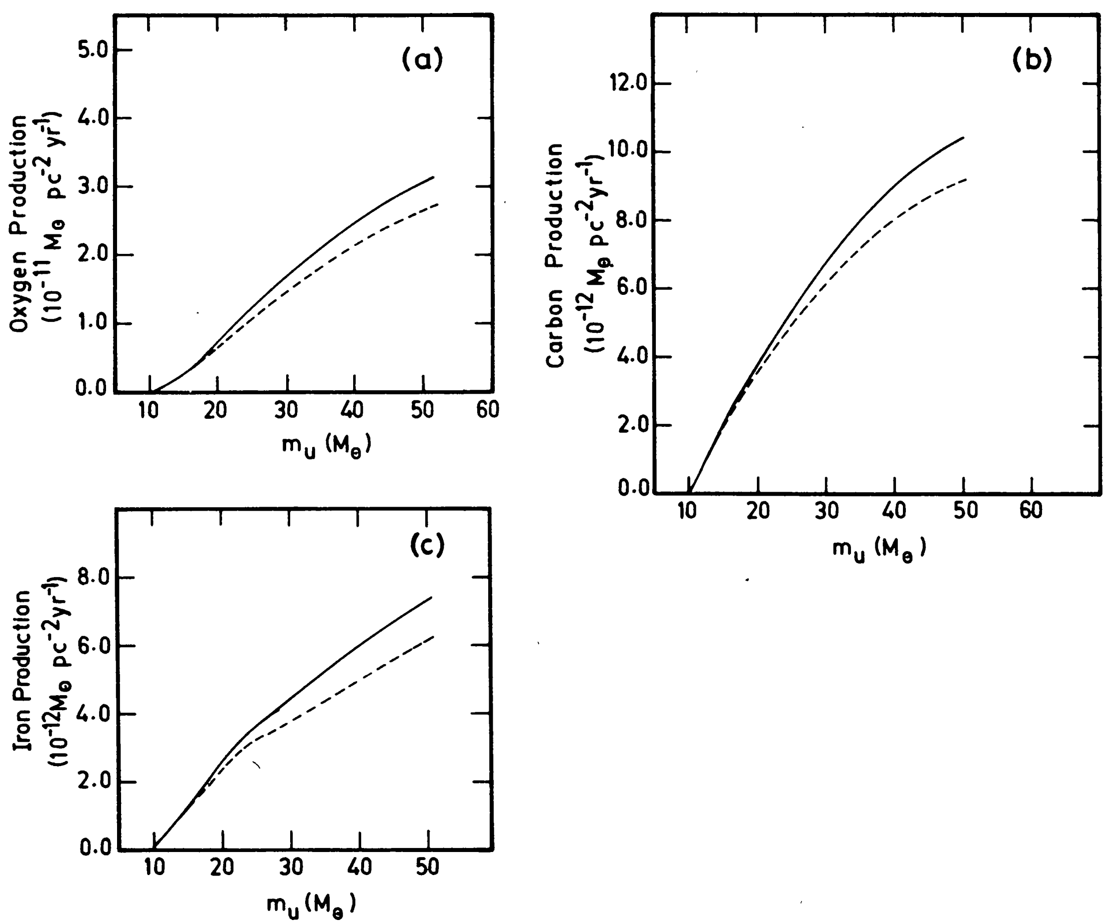

Figure 3. (a) Oxygen, (b) carbon, and (c) iron production rates as a function of m_u. The upper line in each case is calculated with the IMF 1(b) and the lower one with 1(d).

(ii) For the IMF 1(d), the oxygen production rate from massive stars equals the galactic production rate at $m_u = 30$. The corresponding production rates of carbon and iron are $6.1 \times 10^{-12}\ M_\odot\ \mathrm{pc}^{-2}\ \mathrm{yr}^{-1}$ and $3.6 \times 10^{-12}\ M_\odot\ \mathrm{pc}^{-2}\ \mathrm{yr}^{-1}$ respectively. This leads to a deficiency of 19 per cent in carbon production and a maximum deficiency of 27 per cent in iron production. These deficiencies are significant as they provide constraints on the production of iron and carbon from alternative sources, in particular, the IMS.

3.2 *Carbon Production in Planetary Nebulae*

The intermediate-mass stars contribute to element enrichment through the three dredge-up episodes which were first enumerated and quantified by Iben & Truran (1978). The eventual journey of these stars to the stellar graveyard of white dwarfs is critically dependent upon the massloss rate during the final evolutionary stages which controls their ability to reduce themselves below the Chandrasekhar mass limit just prior to carbon ignition in their degenerate core. There is compelling observational evidence to the fact that white dwarfs in many clusters have evolved from stars as massive as 5–8 $M_\odot$ (Romanishin & Angel 1980; Weidemann 1977; Anthony-Twarog 1982; Weidemann & Koester 1983). Planetary nebulae, which represent a transitory phenomenon in the final evolution of these stars, show enhancements of He, C and N (See Torres-Peimbert 1984 for details). French (1983) has derived carbon abundances in a large number of planetary nebulae and concluded that carbon was enhanced in the progenitors by a factor of 2 at the time of ejection of the envelopes. According to him, the enhanced carbon mass in the nebulae observed is $3.6 \times 10^{-3}\ M_\odot$ per nebula. The observed birthrate of planetary nebulae depends sensitively on the adopted distance scale but all the derived birthrates lie in the range $2.4\text{–}12.0 \times 10^{-10}\ \mathrm{pc}^{-2}\ \mathrm{yr}^{-1}$ (Mallik 1984). Thus the total carbon production rate from planetary nebulae amounts to $0.87\text{–}4.3 \times 10^{-12}\ M_\odot\ \mathrm{pc}^{-2}\ \mathrm{yr}^{-1}$. Therefore, planetary nebulae alone can provide 10–50 per cent of the galactic carbon. If massive stars produced carbon at the predicted efficiency, carbon would be over-produced. The models of Renzini & Voli may also be used to derive carbon production rates in the wind phases and planetary nebula ejection phases of stars in the interval $2.5 \leqslant m \leqslant 8$. A variety of values of η and α are used. The results are presented in Table 4. The production rates are too high to be compatiable with observations when $\eta = \frac{1}{3}$ and $\alpha = 0$ and 1; they are in the range of observed values when $\eta = \frac{1}{3}$ and $\alpha = 2$ or $\eta = \frac{2}{3}$ and $\alpha = 1.5$. Thus, whether the observed carbon production rate in planetary nebulae indicates a high massloss rate or an efficient burning at the base of the convective envelope, cannot be decided by looking at carbon production alone. However, the stellar models with appropriate choices of η and α are

Table 4. Carbon production in IMS.

IMF	SFR ($M_\odot\ \mathrm{pc}^{-2}\ \mathrm{Gyr}^{-1}$)	Rate ($10^{-12}\ M_\odot\ \mathrm{pc}^{-2}\ \mathrm{yr}^{-1}$) $\eta = 1/3, \alpha = 0$	$\eta = 1/3, \alpha = 1.5$	$\eta = 1/3, \alpha = 2$	$\eta = 2/3, \alpha = 1.5$
1(b)	4.6	9.87	4.87	1.50	3.00
1(d)	4.6	...	6.30	2.10	3.75

successful in producing the right amount of carbon required by the observations of planetary nebulae. Further, carbon production in massive stars is constrained to perhaps half the observed galactic production rate.

3.3 *The Iron Production Rate and Carbon Deflagration Supernovae*

The situation is quite different with iron. First, apart from the two observations mentioned in the beginning of the section, there is no unambigous identification of iron production in any supernova event (Woltjer 1984). Yet the most plausible model for producing the uniform exponential tail of SN I light curves is the radioactive decay model involving the parent ^{56}Ni whose eventual decay product is ^{56}Fe (Arnett 1979; Colgate & Petschek 1980). Since SN I account for roughly 50 per cent of the net supernova rate, this would make them a major source of iron. Second, although it is generally recognized that SN I originate from relatively low mass stars, the exact nature of their progenitors is not known. It has often been contended that they are terminal explosions of those intermediate-mass stars which ignite carbon in their degenerate cores (see for example Tinsley 1979). On the other hand, observations of planetary nebulae and cluster white dwarfs suggest that few intermediate-mass stars may actually evolve to the point of carbon ignition. However, there are alternative scenarios for producing SN I involving accreting white dwarfs in binary systems with red supergiant companions, which appear to be quite plausible. The theoretical production rate of these events on the assumption that they are carbon detonation of single stars is consistent with the observed rate. Thus, based on the algorithm of Renzini & Voli with $\eta = \frac{1}{3}$, the deathrate of stars becoming supernovae of this type equals 0.059 $\mathrm{pc^{-2}\,Gyr^{-1}}$, and for $\eta = \frac{2}{3}$ it equals 0.027 $\mathrm{pc^{-2}\,Gyr^{-1}}$. The observed SN I rate from Tammann (1982) is 0.029 $\mathrm{pc^{-2}\,Gyr^{-1}}$. If SN I were all carbon detonation supernovae releasing 1.4 $M_\odot$ of iron per event (Arnett 1969), the iron production rate from this source alone would be $4.06 \times 10^{-11}\,M_\odot\,\mathrm{pc^{-2}\,yr^{-1}}$ which is a factor of ten higher than the net galactic production rate given in (3.1). For a uniform birthrate this would lead to an iron abundance of 0.01. It is impossible that the observations are in error by any factor like this. This problem with the overproduction of iron practically rules out the occurrence of carbon detonation supernovae.

In recent years an alternative model for the explosion has been developed principally by Nomoto (1981) in which a deflagration wave rips through the star incinerating the inner portion of the core to iron but ejecting the outer layers of the core as unburned ^{12}C and ^{16}O. The carbon deflagration models have been successful in reproducing the light curves of Type I supernovae. Numerous deflagration models have been computed by Nomoto and collaborators (see Nomoto 1984) and by Woosley, Axelrod & Weaver (1984). The crucial feature of these models relevant to the present discussion is that although the fraction of iron ejected is less, moderate to large amounts of carbon and oxygen are also ejected by them. We have considered only two representative models, Model W7 of Nomoto (1984) and Model 5 of Woosley, Axelrod & Weaver (1984). They provide two extremes of carbon and oxygen production while the mass of iron ejected is roughly similar. These models serve our purpose of highlighting the problems of galactic nucleosynthesis when such events occur at the observed SN I rate. The production rates and the yields of carbon, oxygen and iron are tabulated for both W7 and M5 (Table 5) where we have used the observed SN I rate for the calculation. When

Table 5. Carbon, oxygen and iron production in carbon deflagration models.

	SN I rate: 0.029 pc^{-2} Gyr^{-1}					
	$\dot{\Sigma}_i$ ($M_\odot$ pc^{-2} yr^{-1})		Yield		X/O	
Species	W7	M5	W7	M5	W7	M5
^{12}C	9.28(−13)	9.86(−12)	2.86(−4)	3.03(−3)	0.23	0.95
^{16}O	4.06(−12)	1.04(−11)	1.25(−3)	3.2 (−3)	1	1
^{56}Fe	1.77(−11)	1.42(−11)	5.45(−3)	4.37(−3)	4.36	1.37

these are compared with the results of the previous sections and the constraints imposed by the observations [*cf.* (3.1)], it is obvious that the iron production rate greatly exceeds the requirements. Even if carbon deflagration supernovae were the only source of iron in the Galaxy, at the currently observed SN I rate they would produce several times (2–3) the observed abundance of iron. In reality, things are worse since massive stars also contribute to iron production. Almost all of the galactic carbon could also come from the carbon deflagrations alone which contradicts the results from Section 3.2 that at least half is produced in PN progenitors. This is true of all those models that eject several tenths of solar mass of carbon per event. It is also seen that these models predict reasonable amounts of ^{16}O production, although they may not produce enough to maintain the net galactic production rate. Even then oxygen production in these models is something of an embarassment for nucleosynthesis since all our considerations were based on the assumption that ^{16}O is entirely produced by massive stars. Oxygen has always been regarded as a signature of massive star nucleosynthesis. Observations of Cas A and some other SNR tend to support this view (Kirshner 1982). Theoretically, an examination of the stellar mass fractions returned in the form of various species clearly shows the preponderance of oxygen in the ejecta from massive stars (*cf.* Fig. 2, Audouze & Tinsley 1976). Therefore, substantial oxygen production by lower mass stars will upset many seemingly well-established facts, besides violating our specific assumption here that all oxygen comes from massive stars. The carbon deflagration events clearly infringe upon one or more constraints imposed by observations and conventional wisdom on galactic nucleosynthesis.

A simple-minded solution would be not to have such events at all. However, this is not really a solution since (i) supernovae of Type I do occur in nature and (ii) the carbon deflagration models reproduce a number of key characteristics of observed SN I events without violating any of their observational features (Sutherland & Wheeler 1984). One could perhaps ask by what factor the iron yield from these models should be reduced to satisfy the constraints on the production rates. To choose a particularly favourable case if we assumed that only 50 per cent of the Fe + Si yield as estimated in A78 was ejected as true iron, the rest being unburned silicon, our calculations show that massive stars would still contribute 2.0×10^{-12} $M_\odot$ pc^{-2} yr^{-1} to the iron production rate. If the remainder came from SN I and specifically from carbon deflagrations, the required contribution of these events should amount to at most 2.9×10^{-12} $M_\odot$ pc^{-2} yr^{-1}. Thus, the expected amount of iron per deflagration event is 0.0029/0.029 or 0.1 $M_\odot$. This is about a sixth of what the models predict. However, Sutherland & Wheeler assert that the kinematics of the SN I event requires a minimum of 0.7 $M_\odot$ of incinerated material in the explosion to generate the observed ejecta velocities. Also the problem with excess carbon from these events will still remain. It is unlikely that the SN I rate is grossly overestimated.

A glimmer of hope has been provided recently by the proposed revision of a crucial nuclear reaction rate, namely the rate for the reaction $^{12}C(\alpha, \gamma)^{16}O$. Arnett & Thielemann (1984) quote recent experiments which suggest an enhancement of this reaction rate by a factor of 3–5 over the conventional value and discuss the implications of this upward revision. An enhanced $^{12}C(\alpha, \gamma)^{16}O$ rate enhances the $^{16}O/^{12}C$-ratio after core helium burning and therefore, during the subsequent thermonuclear phases one obtains less carbon-burning products and more oxygen-burning products. It seems logical that in the final yields of massive stars, more oxygen and less carbon would be present as the contribution from zones processed through helium burning. We already found that the yields from A 78 required an upper mass cutoff to the IMF at 28–30 $M_\odot$ to have the theoretical oxygen production rate equal the observed rate in the solar neighbourhood. The same considerations with an enhanced oxygen yield should now lead to an upper mass cutoff which is lower than 28 $M_\odot$. It is difficult for us to say, at the moment, how the iron yield from massive stars is affected. But the contribution of the massive stars to the production of ^{12}C would surely be considerably reduced such that, even if almost all of the galactic carbon originates in lighter stars through carbon deflagration and planetary nebula events, no serious overproduction problem would be encountered.

Finally, if the bulk of the nucleosynthesis in the Galaxy be effected by stars in the mass range 5–30 $M_\odot$, the deathrate of these stars is found to be 0.073 $pc^{-2}\,Gyr^{-1}$ or a galactic average of 10.3 yr^{-1}. The observed supernova rate from Tammann (1982) is 0.063 $pc^{-2}\,Gyr^{-1}$. These rates are equal within the limits of observational uncertainties. Therefore, a typical supernova event is also a typical nucleosynthesis event.

4. Summary and conclusions

In this paper we have attempted to arrive at a consistent picture of galactic nucleosynthesis based on improved data on stellar yields and new determinations of the IMF and the current stellar birthrate. The current rate of nucleosynthesis is high enough to obviate the need for a higher star formation rate in the past to explain the currently observed abundances. The effect of massloss on nucleosynthetic yields is negligible. However, the observed yields are low and to be consistent it is required that stars above a certain mass do not participate in nucleosynthesis. The observed large values of the helium to heavy-element enrichment ratio may be an indirect indication that this actually happens.

If the observational constraints on the current production rates of iron, oxygen and carbon are to be believed, then, stars heavier than 28–30 $M_\odot$ do not effectively participate in nucleosynthesis. Observations of planetary nebulae as well as theoretical dredge-up models of IMS indicate that nearly half the galactic carbon comes from PN progenitors. If carbon deflagration models correctly represent the Type I SN event, substantial amounts of galactic carbon and oxygen could come from them. At the observed SN I rate these models would overproduce iron by a factor of 2 to 3. The role of massive stars in element synthesis is even more suppressed in that case. While there does not seem to be any known way of preventing production of iron in massive stars, the proposed enhancement of the rate of $^{12}C(\alpha, \gamma)^{16}O$ works in the right direction for carbon. This will certainly reduce the carbon production in massive stars considerably and enhance their oxygen yield. The galactic oxygen production rate may then be matched by synthesis in stars up to a mass m_u which is even less than 28 $M_\odot$ which, in turn, will help reduce the iron yield from massive stars. While the carbon production in deflagration events could then account for most of the galactic production, the problem of overproduction of iron due to these events is not totally solved. We have only considered the element synthesis pattern in the galactic disc. Similar considerations may not apply to the halo at all. Observations indicate a very different enrichment history for the halo.

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