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Current Rate of Nucleosynthesis and its Implications

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Abstract. The current rate of nucleosynthesis in the solar neighbourhood is re-evaluated on the basis of Arnett's (1978) stellar yields, the mass loss models of Chiosi, Nasi and Sreenivasan (1978) and the initial mass function determined by Lequeux (1978). If massive stars are held responsible for most of the metals we observe, a higher birthrate of these stars in the past is indicated in view of the low current rate of nucleosynthesis. The intermediate mass stars may not supply the bulk of the metals unless total disruption of their carbon core takes place.

While a declining birthrate is in conflict with the result obtained from the age-metallicity relation of stars, it is supported by some galactic evolution models which interpret successfully the white dwarf mass distribution data. If the constraint of a nearly time-invariant birthrate were strictly accepted, then models of the prompt initial enrichment type are required to explain the observed abundances in terms of nucleosynthesis in massive stars.

Key words: massive stars—nucleosynthesis—stellar birthrate

1. Introduction

Massive stars are generally regarded as the principal sites of primary nucleosynthesis in galaxies. Since they are extremely shortlived, their present birthrate may be directly used to derive the rate of production of the primary synthesis species, once the stellar yields are known as a function of the stellar mass. Arnett (1978) studied the evolution of helium cores of massive stars through silicon burning, electron captures and thermal disintegration and computed the absolute yields of abundant nuclei as a function of the mass of the helium core. In several recent studies these absolute yields have been used to estimate the total yield from a generation of massive stars. These estimates are important in stellar and galactic evolution studies for a number of reasons. First, if the theory of advanced stellar evolution and nucleosynthesis were to be correct, the theoretically computed yields should follow the observed distribution of primary abundances in the solar system. Here it is more to the point to evaluate the ratios of theoretical yields of the various elements and compare them with the observed ratios. Secondly, such a comparison can also be used to gauge the relative importance of stars in various mass intervals (*e.g.* intermediate and high) in the synthesis of various species. Lastly, if the present birthrate of massive stars were assumed to be known with some certainty, the present rate of element production in conjunction with the observed total element abundances would provide essential clues to the overall past rate of nucleosynthesis and hence to the past history of the stellar birthrate. It is this last point which has been the source of a lively debate since the publication of Arnett's singular work on bulk yields (Chiosi 1979; Wheeler, Miller and Scalo 1980).

Arnett (1978) was the first to use the stellar abundances with various choices of the initial mass function (IMF) to evaluate the elemental yield per generation of massive stars. The solar system abundances could be reproduced with reasonable choices of the slope of the IMF. Arnett varied the slope between the classical Salpeter value of 1·35 and a much steeper 3·33 and noted that the relative yields were insensitive to the choice of the slope. However, when the yields were used with the observed birthrate of massive stars according to Ostriker, Richstone and Thuan (1974, hereafter ORT), the current production rate of metals turned out to be about a tenth of the average past rate. This led Arnett to the conclusion that the present rate of nucleosynthesis, though not large, is not negligible either and that the past rate was much higher implying a higher birthrate of the massive stars in the past. This result was compatible with a class of galactic evolution models where the rate of star formation is assumed to vary as the second power of the gas density.

One of the uncertainties in Arnett's calculation was the relation between the mass of the helium core M_α and the initial main sequence mass M of the star that develops this helium core. The M–M_α transformation derived by Arnett was based on evolutionary models without mass loss. Evolutionary sequences with mass loss by stellar wind show large differences with conservative evolution of the same initial mass (Chiosi, Nasi and Sreenivasan 1978; de Loore 1979). In particular, the incorporation of mass loss in evolutionary calculations drastically changes the $M(M_\alpha)$ relation. Models computed with mass loss develop, for the same initial mass of the star, a much smaller helium core than the conservative model. The higher the mass loss rate the smaller is M_α for a given initial M. As a result the fractional mass of various species ejected from a massive star is greatly reduced. The final yields are thus much lower.

Chiosi and Cairnmi (1979), who investigated the effects of mass loss on the nucleosynthetic yields, derived a present rate of nucleosynthesis based upon the ORT birthrate which was a factor of three lower than the rate found by Arnett. Further the theoretical yields with mass loss compared favourably with the solar system abundances only if a Salpeter mass function were assumed, while IMF's with steeper slopes produced much lower yields. The implied variation of the stellar birthrate over the galactic lifetime was considerable, the average past rate derived being almost thirty times higher.

The rate of nucleosynthesis per generation of massive stars is directly dependant upon the birthrate of these stars. The birthrate is determined from observations in the solar neighbourhood of the present-day mass function of main sequence stars (PDMF). The steps to obtain the PDMF from the currently observed luminosity function are outlined in detail in the comprehensive work of Miller and Scalo (1979, hereafter MS). Once the PDMF is obtained, the birthrate of massive stars is easily derived by dividing the PDMF by the main sequence lifetime of each star. For stars whose main sequence lifetimes are of the order of the lifetime of the Galaxy or longer, this simple procedure does not work and one has to know the history of the stellar birthrate.

The birthrate of massive stars determined by MS from the best possible evaluation of the PDMF is considerably higher than the one given in ORT. Also, the slope of the birthrate function (which is the same as the slope of the IMF for these stars) is less steep. Thus the MS birthrate coupled with Arnett's stellar yields predicts a much higher production rate of metals at the present time and to explain the observed abundances as the result of nucleosynthesis in massive stars, no great increase of the birthrate in the past is required. Several independent lines of argument suggest that the average past stellar birthrate has been no more than a factor of 2-3 different than the present one (MS; Twarog 1980). Thus the discrepancy between the predicted variation of the stellar birthrate from nucleosynthetic yields and the lack of such a variation from other evidences is apparently removed by considering the higher MS birthrate. However, when mass loss is taken into account, the discrepancy reappears and a declining birthrate has to be invoked to explain the present solar system abundance distribution (Chiosi 1979).

Observations of chemical abundances in our Galaxy show a linear relation between the helium and heavy element enrichment for a variety of objects (Peimbert 1977). The slope of this line is close to 3. The same relation is found for a large sample of external galaxies (Lequeux *et al.* 1979). In theoretical calculations it has been noted that the current stellar evolution data fail to produce this slope by a factor of 5 or more (Hacyan *et al.* 1976; Mallik 1980). However, if mass loss from the massive stars were taken into account, the agreement is much better. In the latter case, the ability of these stars to produce heavy elements is greatly reduced and the theoretical value of $\Delta Y/\Delta Z$ *is* correspondingly enhanced. Secondly, the heavy element yield p_Z, defined as the ratio of heavy elements newly synthesised and ejected to the mass locked up in stars and stellar remnants per generation of stars, is observationally lower than the theoretical value when mass loss is neglected. Again a very good agreement is obtained if effects of mass loss were incorporated in the theoretical calculation. Therefore, the theoretical nucleosynthetic yields are more meaningful and closer to observational realities when computed with the M–M_α transformation obtained from mass loss models.

A new determination of the IMF of the upper main sequence stars has recently been published by Lequeux (1979). This is based on several recent catalogues, most notably the Michigan catalogue of spectral types (Houk and Cowley 1975) and the catalogue of B stars by Lesh (1968,1972). A different procedure was followed in the assignment of masses to stars of a particular spectral type and luminosity class. The observed HR diagram was superposed on a theoretical one using mass loss evolutionary sequences for massive stars ($M \geqslant 20\ M_\odot$) due to Chiosi, Nasi and Sreenivasan (1978) and Iben's (1967) tracks for intermediate mass stars ($M < 15\ M_\odot$). For each mass range on the main sequence delimited by theoretical tracks, the surface density of stars as a function of mass was directly determined. This is a better way of assessing the masses of the earliest spectral types than using the uncertain and scantily available data from massive binaries. The PDMF thus determined is found to be quite different from the MS data. Further, the IMF is considerably steeper (slope: — 2·0) than the classical Salpeter one. While the agreement of the slope with the one derived in MS is fair for masses above 10 $M_\odot$, the Lequeux IMF is considerably steeper in the mass interval $2{\cdot}5 \leqslant M/M_\odot \leqslant 10$. The birthrate of massive stars derived from this IMF is very much lower than the MS birthrate and is closer to the ORT data although the slope of the ORT birthrate function does appear to be a bit too steep.

The Lequeux IMF should be preferred for a number of reasons. The catalogues used for its determination are the best available. This is also the first time that evolutionary sequences with mass loss have been used to obtain the masses; the flattening of the mass-luminosity relation in mass loss models affects directly the conversion of the luminosity function to the PDMF. Most importantly the Lequeux IMF has been corrected for the presence of a population of evolved O stars which have been involuntarily included in all earlier work. The presence of this population has been clearly established in the recent work of Carrasco *et al.* (1980). Thus the PDMF and hence the IMF for the massive stars are closer to the actual values.

In view of the large difference in the birthrate determined by Lequeux compared to the MS estimate it is worthwhile to have a re-evaluation of the present rate of nucleosynthesis based on the Lequeux IMF and mass loss models for the massive stars. This will then provide a better constraint on the history of the stellar birthrate. It is important to note that the Lequeux birthrate being lower, the present rate of nucleosynthesis based on it is likely to predict a large variation in the birthrate massive stars over the galactic lifetime. Alternatively, if this rate were assumed to be constant at its current value, the hypothesis of massive stars being responsible for the bulk of the nucleosynthesis should be called into question. One has to look elsewhere, possibly at the intermediate mass range ($M \lesssim 8\ M_\odot$), to locate the sites of nucleosynthesis.

In Section 2 we present a comparison of the various PDMF's and the IMF's recently determined. Section 3 describes the theoretical formalism used to calculate the current rate of nucleosynthesis. The implications of this newly derived rate are discussed in Section 4.

2. Comparison of the PDMF's and the birthrates

The PDMF $n(m)$ is defined as the number of main sequence stars in the solar neighbourhood per square parsec per unit mass interval. Here m is the mass of the star in solar units. For massive stars, the initial mass function $\phi(m)$ is directly proportional to $n(m)/\tau_m$ where τ_m is the main sequence lifetime of the star of mass m. The relation between $n(m)$ and $\phi(\mathrm{m})$ may be written as

$$\phi(m) = \frac{n(m)}{\tau_m}\,\frac{1}{\psi_1}, \tag{1}$$

where ψ_1 is the current birthrate in $M_\odot\,\mathrm{pc}^{-2}\,\mathrm{yr}^{-1}$.

In Fig. 1 the PDMF's from the work of MS and Lequeux are shown for comparison. The MS values are taken from their Table 3 and the error bars correspond to the uncertainties quoted by them in their Table 4. Lequeux (1979) has tabulated the

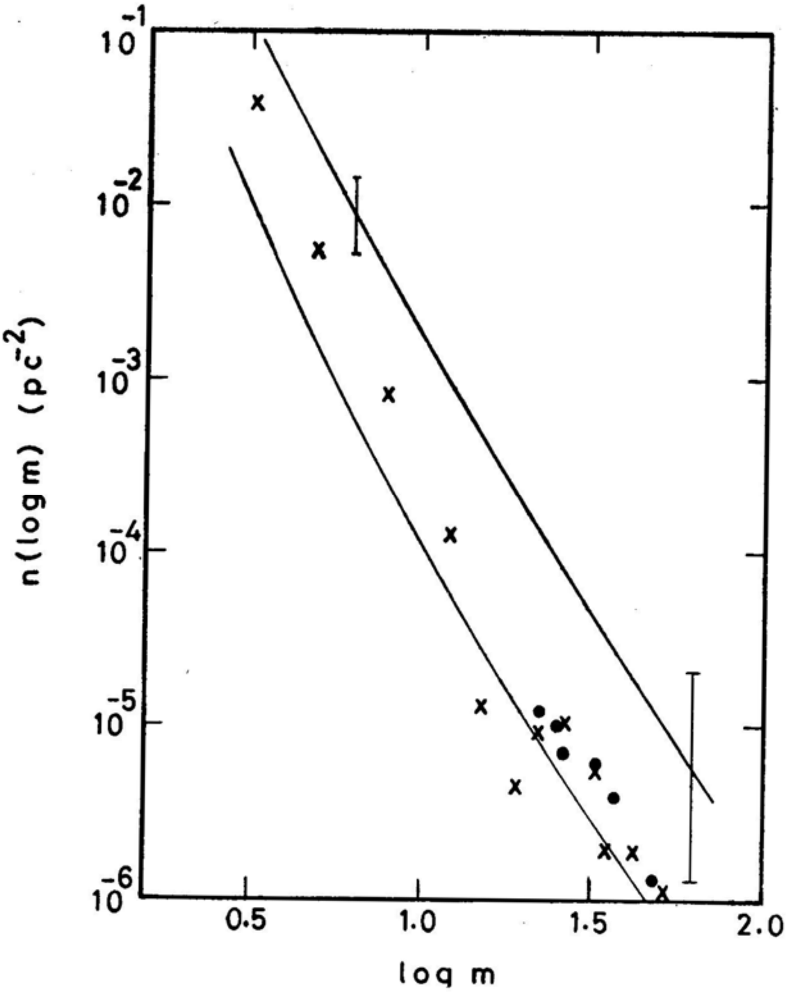

Figure 1. Comparison of the present-day mass functions. Thick solid line (upper) gives the MS data and thin solid line (lower) the Lequeux data. ×, ORT; ●,CGO. See text for details.

logarithmic surface densities (per kpc^2) as a function of mass. We have adopted the values corrected for the runaways and converted them to the same unit as in MS, namely per pc^2 per log *m*. The crosses in Fig. 1 show the controversial ORT data. They certainly imply a steeper birthrate function thereby reducing the fractional mass in massive stars with respect to the total mass in stars. The Lequeux data agree remarkably well with the luminosity function of O stars determined by Cruz-Gonzalez *et al.* (1974, hereafter CGO). This luminosity function includes the earliest O-type stars. We have used the spectral type-M_v calibration given by Lesh (1979) and the mass loss models of Chiosi, Nasi and Sreenivasan (1978) for the case α = 0·90 to convert the CGO data to the corresponding PDMF. This is shown by the filled circles in Fig. 1. It is seen that the MS data give a higher surface density of stars in each mass interval. The values obtained by Lequeux fall below the lower uncertainty limit quoted by these authors. It may be suspected that, since the mass-luminosity relation for the mass loss models is different, the implicit use of this by Lequeux has produced part of the change in his PDMF compared to the one given by MS. However, we have done the exercise of using the mass-luminosity relation from mass loss models and the tabulated stellar densities of MS to derive the PDMF. The change is very little. Hence, the discrepancy between the two PDMF's is real. The mass-lifetime relations used by MS and Lequeux are almost the same. Thus the birthrates derived from the PDMF's have the same relationship to each other as the PDMF's themselves.

In Fig. 2 a plot of the Lequeux birthrate function in units of pc^{-2} Gyr^{-1} m^{-1} is given. The best analytical fit is a straight line with a slope of – 3·0. For the convenience of comparison we have obtained the birthrate at each mass point given in ORT from this plot and expressed the value in units of 10^{-13} pc^{-2} yr^{-1}. Table 1 shows a comparison of the various birthrates. It is to be noted that each entry in columns 3, 4 and 5 of the table is the birthrate n(m) Δm, where Δm is the mass interval centred on the mass of column 2. The Lequeux birthrate is lower than the MS birthrate. Therefore, the rate of nucleosynthesis calculated on the basis of this birthrate is expected to be much lower.

From the plot in Fig. 2 it is also possible to derive a normalised IMF if the current total birthrate in units of $M_\odot$ Pc^{-2} Gyr^{-1} were known. According to Tinsley (1979), the current birthrate has a value of 5 $M_\odot$ Pc^{-2} Gyr^{-1} which also falls almost in the

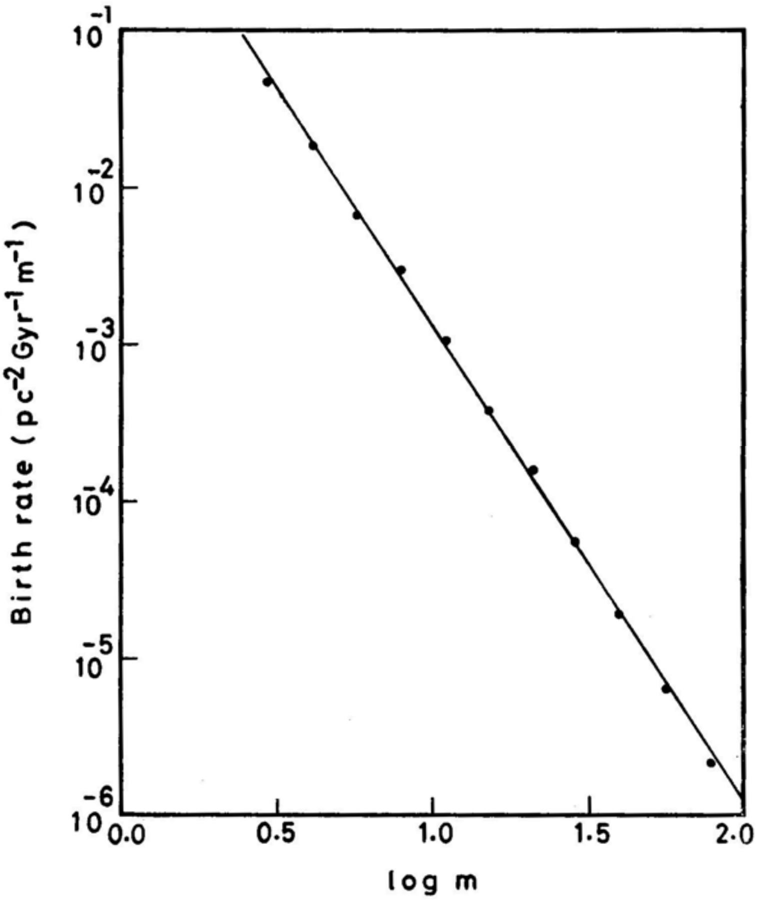

Figure 2. Birthrate function due to Lequeux in pc^{-2} Gyr^{-1} m^{-1} versus log m.

Table 1. Comparison of the current stellar birthrates.

Sp. Type	Mass ($M_\odot$)	Birthrate (10^{-13} pc^{-2} yr^{-1}) ORT	MS	Lequeux
O5	51	1·0	2·1	1·5
O6	42	2·7	4·0	2·2
O7	35	1·3	4·5	3·2
O8	32	2·8	5·4	3·8
O9	26	4·6	11·5	5·9
B0	22	2·5	14·0	8·6
B0.5	19	1·4	22·8	11·1
B1	15	3·1	47·3	18·5
	12	22·0	93.1	29.3
	8	66·0	301·0	66.3
	5	170·0	694·6	195·0

middle of the range of acceptable values suggested by MS. In the present calculations we have assumed the total present birthrate to be 5 $M_\odot$ Pc^{-2} Gyr^{-1} and written for the Lequeux IMF the analytical formula

$$\phi(m) = 0{\cdot}26\, m^{-3{\cdot}0} \tag{2}$$

for $2{\cdot}5 \leqslant m \leqslant 100$, where the masses are in solar units. This IMF is used in Section 3 to calculate the production matrix for a generation of stars and hence the production rate of the primary synthesis species.

3. Rate of nucleosynthesis in the solar neighbourhood

3.1 *Theoretical Formalism*

Following Arnett (1978), let M_j^{ej} denote the mass ejected in the form of species j from a star of initial main sequence mass M_j^{ej} The quantity M_j^{ej} may be expressed in terms of the production matrix element $Q_{ji}(M)$ as

$$M_j^{ej} = M \sum_i Q_{ji}(M)\, X_i, \tag{3}$$

where i denotes the progenitor species and X_i the mass fraction abundance of species i in the stellar material. For the primary nucleosynthesis products,

$$M_j^{ej} = M\, Q_j(M), \tag{4}$$

since $\sum_i X_i \simeq 1$. If $\dot{\sigma}(M)$ be the deathrate of main sequence stars in the mass interval M and $M + dM$, the production rate of species j in the same interval is

$$d\dot{\Sigma}_j = \dot{\sigma}(M)\, M_j^{ej}\, dM. \tag{5}$$

The total production rate of species j from a generation of stars is then given by

$$\dot{\Sigma}_j = \int_{M_1}^{\infty} \dot{\sigma}(M)\, M_j^{ej}\, dM. \tag{6}$$

The lower limit M_1 depends on the element in question and is larger than or equal to M_0, the present turnoff mass in the Galaxy. For the massive stars the deathrate equals the birthrate and

$$\dot{\sigma}(M)\, dM = \phi(M)\, \psi_1\, dM, \tag{7}$$

where $\phi(M)$ is the IMF and ψ_1 the total present birthrate. Thus

$$\dot{\Sigma}_j = \int_{M_1}^{\infty} \phi(M)\, \psi_1\, M Q_j\,(M)\, dM = q_j\, \psi_1, \tag{8}$$

where q_j 's are the integrated elements of the production matrix. The yield of species j is defined as

$$p_j = \frac{1}{1-f} \sum_{i \neq j} q_{ji}\, X_i \simeq \frac{q_j}{1-f}. \tag{9}$$

Here f is the total fractional mass ejected from a generation of stars and depends on the IMF and the relation between the initial mass and the mass of the stellar remnant.

Let us assume that the galactic disk behaved as a closed box after an initial epoch of enrichment. If ΔX_J were the increment of species j over the lifetime of the disk, a uniform production rate $\dot{\Sigma}_j$ acting over this period may be expressed as

$$\dot{\Sigma}_j = \frac{\Delta X_j \Sigma}{T_0}, \tag{10}$$

where Σ is the total surface density of matter participating in nucleosynthesis and T_0 the age of the disk.

However, if the rate of nucleosynthesis were higher in the past owing to a higher star formation rate, equation (10) should be modified to

$$\Delta X_j = \frac{\dot{\Sigma}_j}{\Sigma} \frac{\langle \psi \rangle}{\psi_1}\, T_0, \tag{11}$$

where $\langle \psi \rangle / \psi_1$ denotes the ratio of the past average birthrate to the present one. Equation (11) is the one commonly used to relate the rate of nucleosynthesis to the stellar birthrate.

3.2 *Nucleosynthetic Yields without Mass Loss*

A preliminary estimate of the nucleosynthetic yields with the Lequeux IMF has been made to compare similar estimates by Arnett (1978) and Wheeler, Miller and Scalo (1980). Here the M–M_α transformation adopted by Arnett from stellar models without mass loss has been used and the production rate of the primary synthesis species has been calculated as a function of the spectral type. Table 2 presents the results of this calculation. Columns 4–9 give $\Delta\dot{\Sigma}_j$ as defined in equation (5) for all the various species for which the stellar yields are given by Arnett (1978). The first row in the table is an addition showing the contribution to nucleosynthesis from the hottest spectral types O3-O4. The surface density of these stars is taken from CGO. The mass assignment is uncertain but close to Conti's (1975) calibration. The birth-rate calculated with $\tau_m=10^{6\cdot50}$ yr agrees very well (within 5 per cent) with the value read off Fig. 2 for M=95 $M_\odot$ Due to the rapid fall off of the birthrate function, the contribution of these most massive amongst the stars to the total nucleosynthesis is very small. As seen from the table, the present calculation gives a rate of about a factor of two higher than the one implied by the ORT birthrate and is consistently smaller than the one calculated by Wheeler, Miller and Scalo (1980). The implied variation in the birthrate is about a factor of 4 excepting for He, but He is known to be produced in a pregalactic phase. If, instead of 100 $M_\odot$ pc^{-2} for Σ, the smaller value of 35 $M_\odot$ pc^{-2} advocated by Tinsley (1980) is used, the ratio $\langle\psi\rangle/\psi_1$ is between 1–2, in excellent agreement with the result obtained from the age-metallicity relation of stars (Twarog 1980).

Table 2. Current rate of nucleosynthesis without mass loss form massive stars.

Sp. Type*	M ($M_\odot$)	$\Delta\dot{\sigma}$†	He	C	$\Delta\dot{\Sigma}_j$‡ O	Ne	Mg	Si+Fe	Z
O3-04	95	0·55	4·49	1·54	16·68	1·85	0·86	0·97	21·90
O5	51	1·45	7·44	3·39	17·55	2·19	0·92	1·36	26·41
O6	42	2·18	9·92	4·23	19·18	3·64	1·10	2·09	30·24
O6·5	35	3·24	13·15	5·24	20·09	4·61	1·31	5·08	36·33
O7	32	3·85	14·82	5·62	20·02	4·85	1·39	2·60	34·48
O8	26	5·92	20·25	5·68	17·76	5·62	1·72	2·31	33·09
O9·5	22	8·58	26·56	4·87	14·24	6·60	2·32	2·92	30·95
B0·5	19	11·12	31·69	4·45	14·46	6·67	2·95	3·45	31·98
B1	15	18·53	45·40	4·82	12·97	5·93	3·80	4·26	31·78
B1·5	12	29·25	59·79	5·62	4·88	1·18	1·92	2·95	16·55
$\dot{\Sigma}_j$			233·5	45·5	157·8	44·1	18·3	28·0	293·7
§$\dot{\Sigma}_j/(\dot{\Sigma}_j)_A$			2·1	1·7	1·8	2·0	2·2	2·2	1·9
+$\dot{\Sigma}_j/(\dot{\Sigma}_j)_{MS}$			0·4	0·5	0·6	0·5	0·5	0·5	0·6

*The Sp. Type-Mass calibration is approximate and adopted from ORT and MS.
† The Lequeux birthrate in units of 10^{-13} pc^{-2} yr^{-1}.
‡ The production rate in units of 10^{-13} $M_\odot$ pc^{-2} yr^{-1}.
§Ratio of the rate estimated in the present work to that of Arnett (1978).
+Ratio of the rate estimated in the present work to that of Wheeler, Miller and Scalo (1980

3.3 *Nucleosynthetic Yields with Mass Loss*

In the computation of the rate of nucleosynthesis with mass loss a slightly different procedure has been followed. In an earlier paper (Mallik 1980), we had calculated the chemical evolution coefficients using the stellar nucleosynthesis data from Iben and Truran (1978) and Arnett (1978). The Q_{ij} (M) matrix was calculated based on the M–M_α transformation of Arnett for the massive stars and the Iben and Truran scenario for the low and intermediate mass stars. While the effects of mass loss were thus included for stars of mass lower than 8 $M_\odot$, no attempt was made to do the same for the massive stars. In the present work, we have retained the Q_{ij} (M) prescription of the earlier paper for stars of $M \leqslant 8$ $M_\odot$ and have modified the matrix elements for the massive stars for the mass loss case with the M–M_α transformation obtained by Chiosi (1979). The stellar abundances produced in a helium core of mass M_α are taken from the work of Arnett (1978) but each M_α now corresponds to a larger initial main sequence mass M. It is also assumed that all stars above 12 $M_\odot$ leave a remnant of mass 1·4 $M_\odot$ following a terminal explosion event.

With the IMF given in equation (2) and the new $Q_{ij}(M)$ values the production matrix per generation of stars ranging from 2·5 $M_\odot$ to 95 $M_\odot$ has been calculated. In Table 3 the q_{ij} matrix is displayed. Since we are interested only in the primary nucleosynthesis products, only the relevant matrix elements are shown. For all the species, except C and He the stellar evolution data have nonzero Q_{ij} (M) values only for $M>$ 10 $M_\odot$ C and He, are produced in low and intermediate mass stars also, following the three stages of element dredge-up as enumerated by Iben (1977) and Iben and Truran (1978). The values quoted in Table 3 include the contribution of the less massive stars to the production of C and He.

In Table 4 the production rates of the various species are presented. The change is rather drastic compared to the case without mass loss as presented in Table 2. The change from the rate based on the MS birthrate function and mass loss models

Table 3. Production matrix q_{ij} for a generation of stars.

Product	Progenitor j						
i	H	He	C	O	Ne	Mg	Si+Fe
H	7·25(−2)	...	...	...	...	...	...
He	4·84(−3)	7·70(−2)	...	...	...	...	...
C	9·17(−4)	9·17(−4)	...	...	...	...	...
O	5·76(−4)	5·76(−4)	...	...	...	...	...
Ne	1·45(−4)	1·45(−4)	...	...	...	...	...
Mg	5·46(−5)	5·46(−5)	...	...	...	...	...
Si+Fe	9·95(−5)	9·95(−5)	...	...	...	...	7·84(−2)

Table 4. Current rate of nucleosynthesis with mass loss form massive stars.

$\dot{\Sigma}_J$ (10^{-13} $M_\odot$pc^{-2} yr^{-1})	He	C	O	Ne	Mg	Si+Fe	Z
Mass loss case	179·0	15·5	28·3	7·1	2·7	4·9	58·5
No mass loss	229·0	43·9	141·2	42·3	17·4	27·0	271·8
Chiosi (1979)	364·4	27·9	47·1	16·9	8·0	12·0	111·0
†$\dot{\Sigma}_J/(\dot{\Sigma}_J)_C$	0·49	0·56	0·60	0·42	0·34	0·41	0·53

† The ratio of row 1 to row 3

Table 5. The ratio of the average past birthrate to the current birthrate $\langle\psi\rangle/\psi_1$.

Solar system abundance	He 2·4(−1)	C 4·5(−3)	O 1·1(−2)	Ne 1·2(−3)	Mg 5·6(−4)	Si+Fe 2·0(−3)	Z 1·9(−2)
$\Sigma = 100\ M_\odot\ pc^{-2}$	89·4	19·3	25·9	11·3	13·8	27·2	21·7
$\Sigma = 35\ M_\odot\ pc^{-2}$	31·3	6·8	9·1	3·9	4·8	9·5	7·6

should also be noted. The latter has been taken from Chiosi (1979) and is included in Table 4. Using equation (12) we can now calculate the ratio $\langle\psi\rangle / \psi_1$ For this we have assumed T_0 = 15 Gyr and used two values of the surface density Σ.The results are given in Table 5. The solar system abundances quoted in the table are from Cameron (1973). We find that even for the lower value of Σ, the average past birthrate has to be several times higher than the present one, if massive stars are assumed to be responsible for most of the nucleosynthesis. The lower value of Σ may indeed be the lowest surface density compatible with observations. If a significant fraction of the total mass density resides in low-luminosity dwarfs, Σ should be higher. Thus the variation in the stellar birthrate predicted from the present rate of nucleosynthesis is incompatible with some of the other evidences which suggest a more even birthrate through the galactic history.

4. Implications of the currently observed rate of nucleosynthesis

The present evaluation of the rate of nucleosynthesis casts serious doubts on some of the conclusions of Wheeler, Miller and Scalo (1980). A combination of Arnett's stellar yields for helium cores, the M–M_α transformation obtained from mass loss models and the Lequeux IMF predicts a current rate of nucleosynthesis far below the value quoted by these authors. Various observations of hot stars and interstellar matter in galaxies provide strong evidence for mass loss from massive stars. If we were to accept this fact, then the currently observed heavy element abundance could result from the nucleosynthesis in these stars with a stellar birthrate declining in time. If, on the other hand, the stellar birthrate had not varied by more than a factor of 2 over the past history of the Galaxy, the current rate of nucleosynthesis shows the inadequacy of massive stars in producing the observed metals.

One may look into the mass range 5–15 $M_\odot$, which provides the bulk of the observed supernova rate, to see if these stars also the source of the metals we observe. However, this also has problems. Weidemann (1977) has discussed the evidences of large mass loss in low and intermediate mass stars. Several pieces of observation suggest that stars larger than 5 $M_\odot$ have evolved to white dwarfs after going through an appropriate planetary nebula phase. The birthrate of planetary nebulae is insensitive to the choice of the upper mass limit and does not provide any stringent constraint. The currently observed birthrate is compatible with an upper mass limit in the range of 4–8 $M_\odot$ Abundance analysis of planetary nebulae shows that there is a population of these objects which has most likely come from stars in the intermediate mass range (Peimbert 1978). Most recently, Koester and Weidemann (1980) have analysed the data on DA white dwarfs and have found that the upper limit on stars becoming white dwarfs is higher than 5 $M_\odot$. If all stars of mass up to 8 $M_\odot$ evolve finally to planetary nebulae and white dwarfs, the ability of the intermediate mass stars to produce elements heavier than carbon is severely limited. The entire responsibility of nucleosynthesis would then devolve on stars in the narrow mass interval 8–15 $M_\odot$ One can estimate the average metal yield per star in the mass range 5–15 $M_\odot$ assuming that they supply the bulk of the metals we observe. The result obtained in Section 3 shows that massive stars ($M \geqslant 15\ M_\odot$), at their current birthrate, produce about 5–10 per cent of the total metal abundance. If the rest were to come from 5–15 $M_\odot$ stars, the increment in metallicity over the age of the disk,

$$\Delta Z \sim \langle M_z \rangle \psi_1 \frac{T_0}{\Sigma} \int_5^{15} \phi(M)\, dM, \tag{13}$$

where $\langle M_z \rangle$ is the yield per star in $M_\odot$. With a surface density $\Sigma = 100\ M_\odot\ \mathrm{pc}^{-2}$, and the IMF given in equation (2) this leads to $\langle M_z \rangle \sim 5\ M_\odot$ which is absurd since no star in the mass interval 5–15 $M_\odot$ may develop a core so large and proceed through advanced thermonuclear burning. If instead, $\Sigma = 35\ M_\odot\ \mathrm{pc}^{-2}$, $\langle M_z \rangle \sim 1.7\ M_\odot$, and the requirement of metal production may be satisfied by some models with a total disruption of the carbon core. The present calculation shows that a stellar birthrate declining in time is perfectly compatible with the accepted idea that massive stars produce most of the observed metals. The Lequeux birthrate being lower than the MS birthrate no overproduction of metals results if $\langle \psi \rangle / \psi \geqslant 10$. There is a certain internal consistency in the present calculation which, for obvious reasons, was absent in earlier work. This is in reference to the methods used in the derivation of the IMF by Lequeux which has the mass loss evolutionary sequences already built in.

Koester and Weidemann (1980) have presented a series of models to fit the observed narrow mass distribution of DA white dwarfs. Since a large fraction of the white dwarfs comes from stars formed in the early history of the Galaxy, the white dwarf data could be a sensitive probe into certain aspects of the early galactic evolution. In particular, the mass distribution of white dwarfs depends on the IMF, the birthrate and the relation between the initial and final masses of stars becoming white dwarfs. For a time-invariant IMF of the’ power-law form, it is seen that the observed data may be reproduced with only a variable birthrate function. The best fit comes from models with either the Salpeter IMF or the Larson-Tinsley IMF (Larson and Tinsley 1978) and a time-varying birthrate of the form $e^{-t/5}$ where t is expressed in Gyr. Interestingly enough with a galactic age of 15 Gyr, this amounts to a decline in the birthrate by a factor of 20 which is close to the ratio predicted in Table 5. Although the Lequeux IMF does not extend beyond 2·5 $M_\odot$ and is considerably steeper and we have made no explicit calculation of the white dwarf mass distribution with this IMF, the comparison is made because we have here an independent evidence of a birthrate varying in time.

Recently, Twarog (1980) has determined the age-metallicity relation (AMR) of stars and interpreted it in the light of models of galactic evolution. There is a remarkable discrepancy in this work with the observations of supergiants obtained by Luck and Bond (1980). The actual abundances derived by Luck and Bond are much higher, and in conflict with the AMR derived by Twarog. Twarog has put forth strong arguments in favour of a nearly constant birthrate, the variation in no case exceeding a factor of 2. This result is incompatible with the constraint obtained from nucleosynthetic yields.

In the framework of the simple model of galactic evolution, a high star formation rate in the past implies that a large fraction in the interstellar gas has been astrated by the present time. Consequently, the pregalactic deuterium abundance should be much higher than the observed value. If deuterium were entirely of cosmological origin, this may pose problems for some of the currently accepted models of Big Bang nucleosynthesis. However, the argument favouring a low degree of astration is model dependant and may not be relevant at all, if part of the deuterium were of noncosmological origin, or if the Big Bang nucleosynthesis calculations were wrong in some ways so as to underproduce deuterium (Audouze and Tinsley 1976). The upper limit to the degree of astration is set by the density of visible matter in the universe and a variation of a factor of thirty in the deuterium abundance can be accommodated within this limit (Reeves 1975). The degree of astration implied in the present work does not violate this.

The discussion, so far, is based on the assumption that the IMF is constant through the history of the Galaxy. There is no strong argument for or against the variation of the IMF with time. If the IMF varied any time in the past and were, for example, flatter, the nucleosynthetic yields would be significantly affected. It is conceivable that a flatter IMF in the early history of the Galaxy resulted in a large production of metals and that the IMF steepened later to assume its present form. The birthrate, in this case, need not show any variation. There is some observational evidence that this may have been the case. The analysis of oxygen abundance in metal-poor stars by Sneden, Lambert and Whitaker (1979) shows a substantial overabundance in the [O/H] versus [Fe/H] plot, while the carbon abundance in the same stars follow the line [C/Fe] = 0. The carbon and iron yields from stars are relatively constant over the entire stellar mass spectrum, while the oxygen yield increases dramatically at the higher mass end. The overabundance of oxygen in the old stars suggests that oxygen was produced faster in the early epoch than carbon and iron and may be explained in terms of a flattening of the mass function in the first 2·5 Gyr. Freeman (1977) has shown that the young globular clusters in the Large Magellanic Cloud have remarkably flat IMF's and has argued that their present environment may be similar to the one prevailing in the Galaxy in the early epoch. In case a flat IMF truly represents the situation in the first few billion years of the Galaxy, the metal production rate during the time should have been very high. As the IMF steepened, the mass fraction in massive stars decreased preventing overcooking of the galactic medium. This solution is of the same nature as some of the others invoked to solve the ‘ G dwarf’ problem. The prompt initial enrichment (PIE) model of Truran and Cameron (1971) and the two-component galactic evolution model of Ostriker and Thuan (1975) give similar solutions to the abundance distribution, successfully accounting for the paucity of metal-poor dwarfs (Pagel and Patchett 1975). It may as well be that the present rate of nucleosynthesis indirectly leads us to the same picture, if we accept that the stellar birthrate has been relatively constant during the evolution of the disk.

In conclusion, the current rate of nucleosynthesis is compatible with the idea of massive stars producing most of the metals only if the stellar birthrate decreased with time. The current stellar evolution data as well as observations do not support the premise that intermediate mass stars are the source of the bulk of the nucleosynthesis in the Galaxy. One has to go beyond the purview of the Simple Model and invoke prompt initial enrichment, if the stellar birthrate were to be constant and yet the metals had to come from the massive stars.

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