1992A&A...264..105M

Astron. Astrophys. 264, 105–120 (1992)

ASTRONOMY
AND
ASTROPHYSICS

Stellar yields as a function of initial metallicity and mass limit for black hole formation

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Received June 17, 1991; accepted June 15, 1992

Abstract. Grids of evolutionary star models from 1 to 120 $M_\odot$ with metallicities $Z = 0.001$ and 0.020 are used to derive chemical yields for studies on the chemical evolution of galaxies. The stellar models include the new opacities by Rogers & Iglesias (1992) and take into account, in addition to the usual metal dependent opacity and nuclear effects, the changes of the mass loss rates with metallicity predicted by wind models and also the dependence of the mass loss rates of WR stars on their actual masses. Moderate core overshooting is also accounted for. It has been verified that the model predictions agree with the number statistics of WR and O–type stars in nearby galaxies of various Z.

The wind contributions in He, C, N, O, Ne and heavy elements are given in detail. The total stellar yields including the contributions from the winds, from supernovae and planetary nebulae are also derived for helium and heavy elements. Great care is given to the way the yields are calculated. Schematically we can say that in massive stars, at high Z, large amounts of helium and carbon are ejected into the interstellar medium before being turned into heavier elements. This makes low oxygen, but large helium and carbon yields at high Z. At low Z, most of the new helium and carbon are further processed to oxygen and its descendants, which makes large oxygen, but relatively low helium and carbon yields. An important result of this paper is that the nucleosynthetic production very much depends on metallicity Z.

We also consider the consequences on the yields of various values of the lowest initial mass limit M_{BH} for black hole formation, assuming, in agreement with Burrows (1992), that no or little mass should be lost subsequently to the general relativistic collapse. *The yields in heavy elements strongly decrease with the lowering of* M_{BH}, *since then more heavy elements are swallowed by black holes.* The decrease is however less important at high Z, because lots of heavy elements are anyway ejected by stellar winds and escape. Comparisons with observational estimates of the yields in heavy elements clearly *exclude the case where all the onion skin layers of presupernovae are ejected from all initial stellar masses and suggest a value of* M_{BH} *around 20 to 25* $M_\odot$. This result has only a small dependence on the assumed IMF slope.

Usual nucleosynthetic predictions integrated over the whole stellar mass range and without account of black hole formation generally lead to a ratio $\Delta Y/\Delta Z$ of the relative helium to metal enrichment of about 1. The inclusion of stellar winds may increase $\Delta Y/\Delta Z$ up to a maximum of about 2. These theoretical ratios dramatically differ from the observed estimates in extragalactic low metallicity HII regions by Pagel et al. (1992), who give $\Delta Y/\Delta Z$ in the range of 3 to 6, with a preferred value between 4 and 5. However, *stellar yields integrated over the mass spectrum are able to reproduce the observed* $\Delta Y/\Delta Z$ *if there are black holes formed above* $20 - 25$ $M_\odot$. Also, we emphasize that a value of M_{BH} around $20 - 25$ $M_\odot$ is able to solve the well known problem of oxygen overproduction (cf. Wheeler et al. 1989).

Interestingly enough, a value of M_{BH} at $20 - 25$ $M_\odot$ corresponds to a limiting neutron star mass of about 1.48 to 1.67 $M_\odot$ according to the calibration by Thielemann et al. (1992) or up to about 2 $M_\odot$ according to Woosley's (1986). It is also emphasized that at $Z = 0.02$, very large initial masses may probably not lead to black holes, due to their too low remaining masses.

Key words: evolution of stars – evolution of galaxies – primordial helium – WR stars – black holes

1. Introduction

Many recent developments have been made in the theory of the chemical evolution of galaxies, as well as in the comparisons with the observed abundances in metal deficient stars (for recent works and reviews, see Gilmore et al. 1989; Matteucci 1987, 1989, 1991; Pagel 1987, 1989ab, 1992; Tayler, 1990; Truran 1984, 1988, 1991; Wheeler et al. 1989). The results of chemical evolution depend very much on the history of star formation. Such is the case, for example, for relations like the abundance ratio [Fe/H] as a function of time, or like the ratio [O/Fe] as a function of [O/H]. Such relations depend on the past IMF (initial mass function) and SFR (star formation rate), on the presence of bursts, on the interval of time between them (cf. Gilmore & Wyse 1991; Matteucci & Brocato 1990). In this way, as shown by Matteucci and Brocato, the curves of [O/Fe] as a function of [O/H] are different for the elliptical galaxies, the galactic bulge, the solar vicinity or the Magellanic Clouds. In addition to specific assumptions on the SFR, the IMF, the infall rate, etc. ..., the key effect in the interpretation of past chemical abundances still rests on the fact that more massive stars have smaller lifetimes. In the early phases of galactic evolution, only massive stars contribute to the chemical enrichment due to their short lifetimes. As time goes, smaller stellar masses come into the game: firstly, only SNII contribute to the enrichment (mainly in O, Ne–Ca elements and r–process elements), then appears the production of the intermediate mass stars (with mainly C, N and s–process elements); they are followed by the contributions from supernovae SNIa (mainly Fe injection). Thus, the ages at which stars of a given mass release their nucleosynthetic production are considered as the major and even as the only effect regarding the changes of stellar yields as a function of time.

The aim here is to show that there are other stellar effects, generally ignored, which strongly influence the stellar yields. The first main point is that the nucleosynthetic production, particularly in massive stars, changes very much with initial metallicity, i.e. with time in the evolution of galaxies. Thus, the yields for the early stages of galaxy evolution should not be taken as identical to the yields obtained at solar composition.

Metallicity generally influences stellar evolution mainly through bound–free and line opacities. Thus the structural effects of opacities make the evolution of low mass stars in globular clusters different from that of solar type stars. For massive stars, the main opacity source in the interior is electron scattering, which is independent of metallicity. Therefore, metallicity has little direct structural effects in massive stars. However, bound–free and line opacities are important in the very outer layers of massive stars. In this way, metallicity influences the outer opacities and therefore the mass loss rates by stellar winds in massive stars (cf. Abbott 1982; Kudritzki et al. 1987, 1991). In turn, mass loss has a great influence on stellar evolution and nucleosynthesis (cf. Chiosi & Maeder 1986). Thus, in massive star evolution, metallicity mainly comes into play through its effects on the mass loss rates. This kind of effect has been incorporated in new grids of evolutionary models from 1 to 120 $M_\odot$ for $Z = 0.001$ and 0.020 (cf. Schaller et al. 1992), computed with the new opacity tables by Rogers & Iglesias (1992) and Kurucz (1991). These models lead to new chemical yields, greatly depending on the initial metallicity, the differences being large enough to require a re–examination of some problems in chemical evolution.

Another major effect of great potential influence on the chemical yields concerns the formation of black holes. We do not know yet what is the range of initial stellar masses leading to black holes. However, it is clear that if black holes form from stars with initial masses above some value M_{BH} and swallow some of the so–called onion skin layers present at the time of the pre–supernova, this will greatly affect the resulting nucleosynthetic yields. There are still many uncertainties about this problem which is discussed in section 7 below, where several consequences of various assumptions on black hole formation are also examined and compared to the observations.

The last observable stage in massive star evolution before neutron star or black hole formation is the Wolf–Rayet (WR) stage. Thus, the statistics of WR star numbers in galaxies of different metallicities Z are an important test of the models at various Z and of the values of the final stellar masses. In this respect, the theoretical predictions of the number ratios of WR/O–stars of WC/WR and WC/WN subtypes have been made and compared to the observations in galaxies of the Local Group (cf. Maeder 1991). The very good agreement gives support to the adopted dependence of the mass loss rates on Z. The Z–dependent models were able to account for the particular distribution of the WC subtypes in galaxies (cf. Smith & Maeder 1991). Also, the behaviour of the extreme WO stars, which exhibit the products of advanced $^{12}C(\alpha, \gamma)^{16}O$ reaction, compares quite well with model predictions.

Section 2 presents the relevant model ingredients. Section 3 gives data on the final masses, on M_α and M_{CO}, i.e. the masses of the helium and CO cores. In Sect. 4 some basic equations about the yields are clarified and the results on the nucleosynthetic contributions from the stellar winds are shown. In Sect. 5 we present the detailed procedure used in the derivation of stellar yields from final ejecta (supernovae, planetary nebulae). The results on the overall stellar yields are given in Sect. 6. In Sect. 7 we examine the impact of black hole formation on the chemical yields in relation with observations.

2. Brief note on model ingredients

Models have been computed (cf. Schaller et al. 1992) for initial stellar masses of 1, 1.25, 1.5, 1.7, 2, 2.5, 3, 4, 5, 7, 9, 12, 15, 20, 25, 40, 60, 85 and 120 $M_\odot$ and initial metallicity Z and helium content Y, $(Z, Y) = (0.001, 0.243)$ and (0.020, 0.300). The evolution has been followed up to the end of central C–burning for massive stars, up to the end of the E–AGB phase for intermediate mass stars and up to the He–flash for low mass stars. Let us mention some particularly relevant points in the model ingredient of these new sets, which represent a total of more than 80'000 individual stellar models.

- New radiative opacities by Rogers & Iglesias (1992) have been included for the available range of X, Y, Z. The changes with respect to the Los Alamos 1977 opacities are quite large: they typically amount to a factor of 3 at 300'000 K for solar metallicity. Most outputs of stellar evolution are significantly modified by these opacity changes. At low T, i.e. below 6000 K, radiative opacities by Kurucz (1991) also including the main molecular lines have been accounted for.
- The opacities critically influence the determination of the helium mass fraction Y in the Sun. With the low opacity data by Cox & Stewart (1970), the Y value required to account for the solar L was 0.25 (cf. Bahcall et al. 1982). With the slightly larger opacities from the Los Alamos Opacities Program (cf. Huebner et al. 1977), the He–content of the Sun was found to be $Y = 0.28$ (cf. Lebreton & Maeder 1982). Now, the larger opacities by Rogers & Iglesias (1992) again lead to an increase in Y (since helium is more transparent than hydrogen). Test models made with $Z = 0.0188$, the metallicity of the Sun (cf. Anders & Grevesse 1989), have been performed and a value of $Y = 0.29 - 0.30$ has been found to match the solar luminosity (cf. Guenther 1991) depending on the equation of state used.
- Interestingly enough, if we consider the recent value of the cosmological helium $Y_P = 0.228$ (cf. Pagel et al. 1992), we see that the present solar helium content implies a relatively high ratio $\Delta Y / \Delta Z \geq 3$ of helium–to–metal enrichment during galactic evolution. This ratio is consistent with the recent value found by Pagel et al. (cf. Sect. 7.3 below).
- An updating of nuclear cross–sections has been made, in particular for $^{12}C(\alpha, \gamma)^{16}O$ (cf. Caughlan et al. 1985; Descouvemont 1989). New rates of neutrino losses by Itoh et al. (1989) are included.
- Substantial changes in the algorithms used for computing the chemical changes have been brought (cf. Schaller et al. 1992). Partial ionisation of the main heavy elements is treated explicitely. Also, the optically thick winds of WR stars are treated in the framework of the so–called modified CAK theory (cf. Castor et al. 1975; Kudritzki et al. 1989).
- Extensive comparisons between models and observations show the need of only moderate overshooting from convective cores. With the new opacities, an overshooting distance of 0.20 H_p is well suited (cf. Schaller et al. 1992). A consequence

of this necessary assumption is that our models have slightly larger CO cores than other models (cf. Sect. 3 below).

- Curves of equal mass loss rates $\dot{M}$ over the HR diagram have been calibrated by de Jager et al. (1988) for Pop. I stars. They have been used for models with $Z = 0.02$ by Schaller et al. (1992); for stars with $M > 20\ M_{\odot}$ at $Z = 0.020$, a second set (Tables 1A to 6A in Schaller et al.) has been computed with $\dot{M}$–rates increased by a factor of 2 in post–MS stages. This second set better reproduces the minimum luminosity of WR stars, the WR/O number ratio and the chemical abundances of WR stars (cf. Schaerer & Maeder 1992). Thus we consider it as the basic set of models for obtaining the yields at solar composition. However, the tables in the present paper also give, for comparison purposes, the data for the usual lower mass loss rates at $Z = 0.020$. For different Z–values, the mass loss rates by de Jager et al. (1988) are scaled according to $(\dot{M}_z/\dot{M}_o) = (Z/Z_o)^{\xi}$, where the index "o" refers to $Z = 0.020$. A factor $\xi = 0.5$ has been taken, as indicated by stellar wind models (cf. Kudritzki et al. 1987, 1991).
- For WR stars we have specifically taken into account the recent results on the dependence of the mass loss rates $\dot{M}$ on the actual mass M of these stars (cf. Langer 1989). This strong $\dot{M} \sim M^{2.5}$ dependence applies to the early WN stars (no hydrogen left, nearly pure He–stars) and to the WC stars (He, C, O stars). The same relation is taken whatever the initial Z, since the main composition differences between the WR subtypes do not result from initial metallicity, but from the properties of the bare cores. The relation between $\dot{M}$ and M for WR stars leads to much more consistent stellar properties (cf. Langer 1989). The masses of these new WR models are also in much better agreement with the results from binaries (see also St. Louis et al. 1988), and the new WR luminosities obtained enable us to solve the problem brought about by the relatively low WR luminosities found by Schmutz et al. (1989). Interestingly enough, a positive relationship between $\dot{M}$ and M for WR stars also receives support from the study of vibrational instability (cf. Maeder 1985). The consequence of Langer's relation is the existence of a huge mass loss rate at the entry into the WNE and WC phases; then, as the actual WR masses rapidly decline, the mass loss rates also decrease. The net result is that for most of the WR lifetimes the actual WR masses are rather small. In particular, the final stellar masses are expected to be very small. This is especially the case for high Z models, because due to the relatively high mass loss rates in the pre–WR stages, the entry into the WR phase occurs relatively early in evolution, so that the high WR mass loss rates have plenty of time to strongly reduce the WR masses.

3. Final stellar masses, masses M_{α} and M_{CO}

Here we present some global stellar properties relevant for the chemical evolution of galaxies. Firstly, we show the values of the final stellar masses, which determine the kind of supernova explosions (cf. Nomoto et al. 1991) and the kind of remnants. Fig. 1 illustrates the values of the final masses as a function of initial masses and Z, detailed numerical data for massive stars being provided in Table 1. Fig. 1 also shows the lines for constant mass evolution, and for constant WR mass loss rates, i.e. $\dot{M} = 2.8 \cdot 10^{-5}\ M_{\odot}\ \mathrm{yr}^{-1}$ as taken by Maeder & Meynet (1987) and for the two cases considered by Schaller et al. (1992). This figure beautifully shows, for the physical reasons discussed above, how small the final WR masses are for models with $Z = 0.02$, whether or not the high rates in post–MS phases are taken. Fig. 1 well illustrates the fact that *evaporation by stellar winds is a dominant factor in massive star evolution at solar or higher Z values.*

Table 1. Final masses (solar unit)

M	Z=.001	.020	.020 Lower $\dot{M}$
120	81.12	2.35	7.62
85	61.78	3.49	8.98
60	46.82	2.96	7.83
40	38.34	3.57	8.12
25	24.51	11.30	15.58
20	19.38	13.95	16.52
15	14.85	13.59	
12	11.92	11.52	
9	8.96	8.60	
7	6.98	6.80	
5	4.99	4.92	

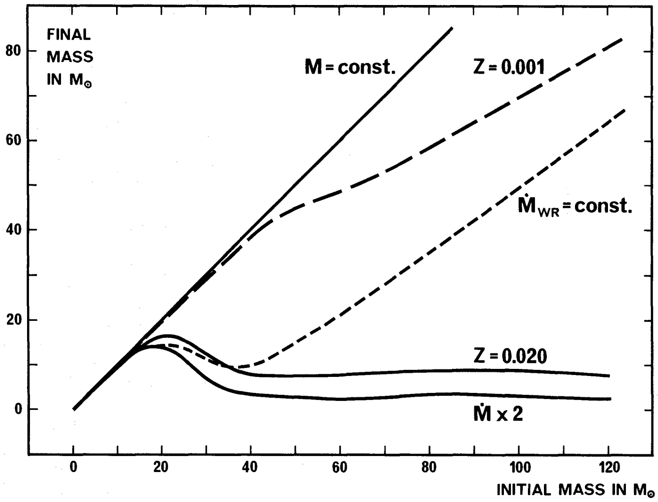

Fig. 1. The final stellar masses as a function of initial stellar masses and metallicities. For massive stars, this is the mass in the pre–supernova stage; for intermediate mass stars, the mass at the end of the E–AGB; for low mass stars, the mass at the He–flash. At $Z = 0.020$, two cases are shown with mass loss rates differing by a factor of 2 in post-MS stages

3.1. Masses M_{α}

From the point of view of the chemical yields, the masses M_{α} of the helium cores are more significant than the final masses and they have often been considered as the main parameter determining the chemical yields (cf. Arnett 1978, 1991; Nomoto & Hashimoto 1986; Nomoto et al. 1991). This is especially the case when the authors only follow the evolution of helium cores. They are thus using a relation $M(M_{\alpha})$ to transfer their results for helium cores of mass M_{α} to a scale of initial masses M. It has been emphasized (cf. Maeder 1981) that this procedure may be unsafe for several reasons. **1)** Some new synthetized matter may be dreged–up into deep external convective envelopes. **2)**

Mass loss in WR stages critically affects the M(M$_\alpha$)–relation. **3)** This procedure ignores the chemical yields from the winds. **4)** The mass M$_\alpha$ may increase or decrease (depending on mass loss) during the helium burning phase, so that the value of M$_\alpha$ at the beginning of the helium burning phase is not very relevant for nucleosynthesis; thus it is better to consider the value of M$_\alpha$ at the end of the He–burning phase or of the C–burning phase. This is done in Table 2. All this shows that great care has to be taken in deriving chemical yields only from the computations of helium cores.

Nevertheless, as M$_\alpha$ is still often used, we show the relations M(M$_\alpha$) for our models with $Z = 0.001$ and 0.020, and compare them in Fig. 2 to the M(M$_\alpha$) relations derived from models by Woosley & Weaver (1986) and by Nomoto & Hashimoto (1986; cf. Nomoto et al., 1991). We notice the following points. — For high mass stars, mass loss may lead to a drastical reduction of M$_\alpha$. — For intermediate and low mass stars, M$_\alpha$ is larger at lower Z. This is due to the fact that at lower Z, central T are higher during MS evolution and the convective cores are therefore larger. — The comparisons of our M$_\alpha$–values with those by Woosley & Weaver (1986) and by Nomoto & Hashimoto (1986) show that our values in the range of 10 – 20 $M_\odot$ are slightly larger, by about 0.02 and 0.05 dex respectively. This is due to the account of a small overshooting in our models.

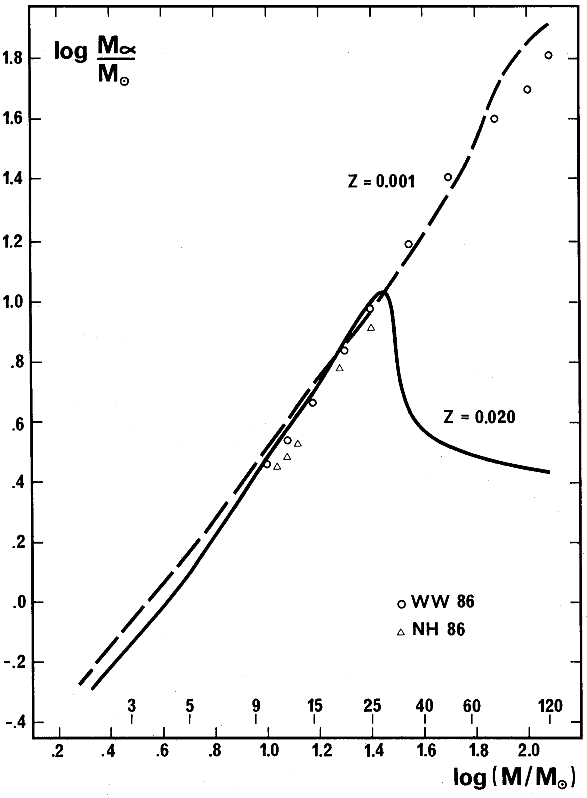

Fig. 2. Relation between the mass M$_\alpha$ of the He–core, at the end of the C–burning phase, and the initial mass. The cases with $Z = 0.001$ and 0.02 are shown. The values by Woosley & Weaver (1986) and by Nomoto & Hashimoto (1986) for solar composition are shown

3.2. *Masses M_{CO} and observational tests*

The mass M$_{CO}$ of the CO cores formed at the end of the C–burning phase (or at the end of the He–burning phase for stars which do not ignite carbon) is even a much more significant mass for the nucleosynthesis of heavy elements, since it is not subject to further mass loss effects and it critically determines the amounts of heavy elements produced. Table 2 gives the values of M$_{CO}$ (cf. also Fig. 3 and 4). Our values are compared in Fig. 3 with those by Woosley & Weaver (1986) and by Thielemann et al. (1991; cf. also Nomoto & Hashimoto 1986). We notice that a 15 $M_\odot$ star in our models has the same M$_{CO}$ as a star of about 15.8 $M_\odot$ by Woosley and Weaver or a 17.4 $M_\odot$ by Thielemann et al. (1991). Thus we see that our hypothesis of moderate overshooting has rather limited consequences on the mass of the CO cores.

Table 2. Masses of the helium and CO cores (solar unit)

Mass	M$_\alpha$		M$_{CO}$	
Z =	.001	.020	.001	.020
120	81.12	2.35	58.73	2.35
85	61.78	3.49	38.12	3.49
60	28.09	2.96	24.75	2.96
40	16.87	3.57	13.88	3.57
25	9.38	9.65	6.94	7.20
20	7.29	7.17	4.94	4.94
15	5.11	4.84	3.12	2.97
12	3.91	3.72	2.25	2.10
9	2.82	2.56	1.55	1.38
7	2.08	1.86	1.11	1.01
5	1.44	1.19	0.88	0.72

Owing to the importance of M$_{CO}$ in Sect. 5 below, let us mention and perform some more observational tests. For massive stars, bare CO cores are WC stars and extensive tests (cf. Maeder 1991) provide a good anchor for the models of massive stars. For the intermediate mass stars, let us examine the initial–final mass relation by Weidemann (cf. 1987, 1990). Firstly, let us recall that Weidemann concludes that models with overshooting better reproduce the observed relation between initial and final masses. In Fig. 4, the "observed" initial–final mass data for white dwarfs in galactic open clusters are presented (cf. Weidemann 1987). On the theoretical side, white dwarfs may be considered as CO cores, with various C/O ratios depending on the initial mass (cf. d'Antona & Mazzitelli, 1990). According to these authors, the low mass stars (M$\leq$ 1 $M_\odot$) may lead to He–cores, while stars with initial masses close to M$_{up}$ (minimum mass for C–burning, i.e. about 7.5 $M_\odot$ in the present models at $Z = 0.02$) are likely to be O – Ne – Mg white dwarfs, i.e. stars revealing more advanced stages of nuclear processing. Thus, it is reasonable to compare the white dwarf masses with the theoretical M$_{CO}$ only in a limited range of initial masses, say from about 2 to 7 $M_\odot$, the situation being less safe at both ends of the interval. This comparison is made in Fig. 4, where we have plotted the values of M$_{CO}$ at the end of the E–AGB phase, M$_{CO}$ being not expected to change significantly in the late AGB phase, which is very short. The good consistency shown in Fig. 4 gives support to the present models and in particular to the sizes of the CO cores. Weidemann (1987) has shown that for a given initial mass, the WD masses should

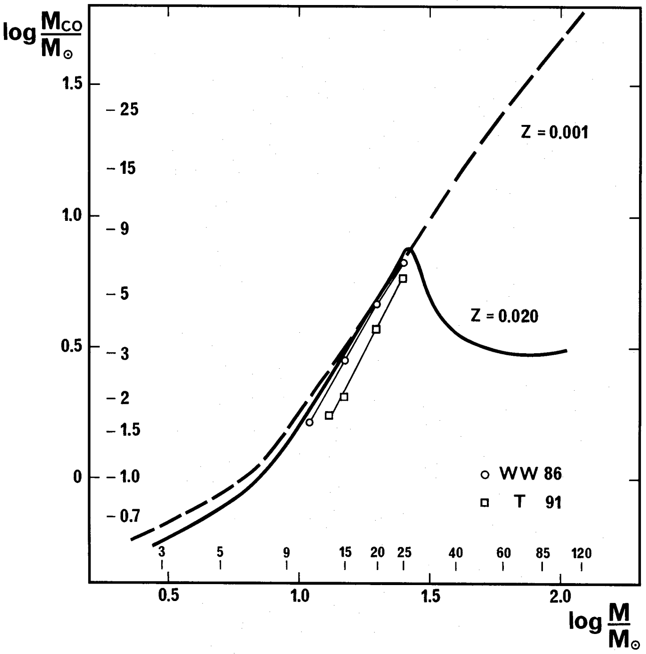

Fig. 3. Relation between the mass M_{CO} of the CO–core, at the end of C–burning phase, and the initial mass for different metallicities. The values by Woosley & Weaver (1986) and by Thielemann et al. (1991) are also shown

be larger by about 0.1 $M_\odot$ in the LMC than in the Galaxy. We also notice from Fig. 4 that this trend is in agreement with the present metallicity dependence of M_{CO} at a given initial mass.

4. The chemical yields and the wind contributions

4.1. A critical remark on the basic equations

The astronomical community has generally adopted, with very good reasons, the clear notations and valuable developments by Tinsley (1980) about chemical evolution of galaxies. Like many authors, we have used them (cf. Maeder 1981). However, a re–inspection of the basic equations shows us that a correction directly concerning the definition of the yields has to be brought to equation 3.9 by Tinsley and the resulting ones. The total E_{zm} of the heavy elements ejected by a star of initial mass m was written

$$[(m - w_m - mp_{zm})\, Z(t - \tau_m) + mp_{zm}] \tag{1}$$

which appears in the bracket term of equation (3.9) by Tinsley (1980), where w_m is the remnant of initial mass m, p_{zm} the mass fraction of a star of mass m converted to metals and ejected, and $Z(t - \tau_m)$ the initial Z content (present time minus star lifetime). Instead of Z, we may have any element i.

Indeed, this bracket term, i.e. the total E_{zm} of the ejecta of a star of initial mass m should just have been written

$$E_{zm} = (m - w_m) Z(t - \tau_m) + mp_{zm} \tag{2}$$

The first term is the ejected mass of the heavy elements initially present, the second term is the ejected mass of the newly synthetized elements. If an element is destroyed by nuclear processing, mp_{zm} is negative. There is no reason in (1) to again substract mp_{zm}. The proof is that if we make the sum of all elements i ejected, one must find $(m - w_m)$

$$\sum E_{im} = (m - w_m) \sum X_i(t - \tau_m) + m \sum p_{im} \tag{3}$$

$\sum X_i(t - \tau_m) = 1$ if all elements are counted, and $\sum p_{im} = 0$ since there is overall mass conservation. Thus, one obtains

$$\sum E_{im} = m - w_m \tag{4}$$

an expression which would not be found with equation (1).

As a consequence, many further equations of chemical evolution should be modified. In particular, one has in the approximation of instantaneous recycling

$$M_{gas} \frac{dX_i}{dt} = y_i(1 - R)\psi \tag{5}$$

rather than

$$M_{gas} \frac{dX_i}{dt} = y_i(1 - R)\,(1 - X_i)\,\psi \tag{6}$$

where y_i is the yield and R the returned fraction (see below). This undesired term was written by Tinsley (1980; cf. eqn. 3.14), or by myself (Maeder, 1981; eqn. 8). Then Chiosi (1986) developed several expressions also containing this "unnecessary term". For heavy elements, the consequences of (6) are generally small (except for galactic bulges); however, for helium the effect is large. An important consequence of the present clarification is that the ratio dY/dZ of the helium–to–metal enrichments is just the ratio of the yields

$$\frac{dY}{dZ} = \frac{y_y}{y_z} \tag{7}$$

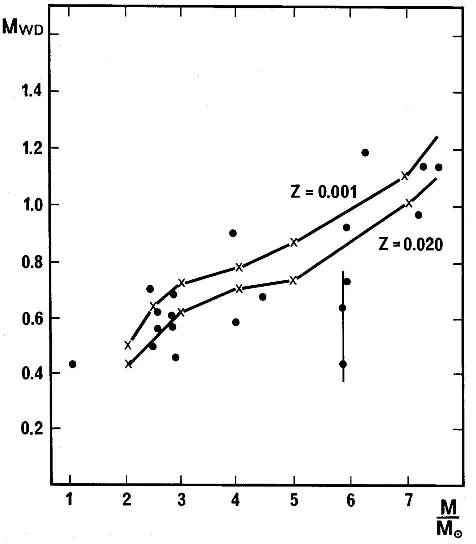

Fig. 4. Values of the white dwarf masses in function of the initial masses from Weidemann (1987). The relations between M_{CO} and initial masses are shown for $Z = 0.001$ and $Z = 0.020$. For reasons given in the text, the interval to be considered is from 2 to about 7 $M_\odot$. The Sanduleak–Pesch binary is not included. The two values of 2451–6 with their error bar are shown

without any additional factor.

The stellar yield p_{zm}, according to eqn. 2 above, is just the difference between what is ejected and what was initially present. It is the sum of the wind and supernova contributions (cf. Maeder 1981).

$$p_{zm} = p_{zm}^{wind} + p_{zm}^{SN} \tag{8}$$

with

$$mp_{zm}^{wind} = \int_0^{\tau(m)} \dot{M}(m,t)\,[Z_s(t) - Z_0]\,dt \tag{9}$$

$$mp_{zm}^{SN} = \int_{remnant}^{m(\tau)} [Z(m') - Z_0]\,dm' \tag{10}$$

where $\dot{M}$, Z_s, $Z(m')$, Z_0, τ and $m(\tau)$ are respectively the mass loss rates, the mass fraction of element Z at the surface, the mass fraction of element Z at the mass level m' in the star, the initial mass fraction of element Z, the age of the star and the remaining mass at age τ. Instead of Z, one may also consider the yields for any element i.

The net yields y_i or yields are essential parameters for galactic chemical evolution, because in many galactic models the observed abundances depend on simple functions of y_i. The net yield is the mass of the new element i ejected by all stars per unit mass of matter locked into stars

$$y_i = \frac{1}{(1-R)} \; \frac{\int_{m_\ell}^{m_u} mp_{im}\,\varphi(m)dm}{\int_{m_\ell}^{m_u} m\varphi(m)dm} \tag{11}$$

The returned fraction R is the fraction of mass that has formed stars and then been ejected.

$$R = \frac{\int_{m_\ell}^{m_u} [m - w(m)] \quad \varphi(m)\,dm}{\int_{m_\ell}^{m_u} m\varphi(m)\,dm} \tag{12}$$

$\varphi(m) = dN/dM$ is the IMF defined between the upper and lower masses m_u and m_ℓ.

4.2. The wind contribution to the yields

The wind contributions for He, C, N, O, Ne and Z (total of heavy elements) have been integrated over the stellar lifetimes with the above correct expressions. The amount of mass ejected mp_{im}^{wind} is given in Table 3 for various elements i in terms of solar mass. We notice the following:

- The stellar yields in helium from the winds are larger for larger masses and Z, as expected, since strong stellar winds take away a lot of new helium. This is particularly the case for models at $Z = 0.020$ with the higher $\dot{M}$–rates.
- For carbon, the same general trend is present for the same reasons. It is interesting to see that carbon may also be taken away before being destroyed; this occurs in WC stars at $Z = 0.020$ which eject considerable amounts of carbon in their winds. The comparison of both sets at $Z = 0.020$ is interesting. The case of higher $\dot{M}$–rates at 120 $M_\odot$ produces less C (and O), since most of the mass has gone in the form of He in the wind.
- At $Z = 0.020$, more oxygen is ejected in the wind of the models of massive stars with the lower $\dot{M}$–rates. This behaviour was already found by Maeder (1990; cf. Smith & Maeder 1991): if massive stars enter later the WC stage, more He has been processed to carbon and oxygen and the wind ejecta of these elements are therefore larger.
- The models at $Z = 0.001$ do not loose enough mass to enter the WC stage and to eject carbon and oxygen. In this case, as a result of the CNO cycles, part of the initial contents in C and O are turned to nitrogen, which explains the small negative yields in C and O. The same situation occurs for models of lower masses at $Z = 0.020$.
- In all the present models, N is only created as a secondary element. Thus, the wind contributions are larger at high Z. Models with diffusion would likely be able to create some primary nitrogen, and then the situation would be different (in this context, see Matteucci 1986a).
- The case of Ne is very special. At high Z, the main neon isotope is Ne–22, the daughter elements of CNO; very little Ne–20 is made as the products of He–burning are revealed at an early stage of processing. The models at $Z = 0.001$ do not eject neon since they do not enter the WC stage. However, as shown by Maeder (1990, 1991), if models at low Z may enter the WC stage, there is very little Ne–22 ejected, but a lot of Ne–20, since the products of helium burning are ejected at a very advanced stage of nuclear processing (see Figs. 1 and 2 in Maeder 1991). Thus, the relative production of ^{22}Ne/^{20}Ne is likely to increase by an enormous factor (say 10^4) during the chemical evolution of galaxies and it would be magnificient to be able to have radio observations of this isotopic ratio through the Galaxy.

5. Derivation of the stellar yields

The range of stellar masses from 1 to 120 $M_\odot$ considered here is large and a variety of situations occurs. This means that great attention has to be paid in the proper derivation of stellar yields. In this section we shall clearly specify the procedure which is adopted here.

Let us first discuss the masses of the remnants which play an important role in the values of the stellar yields since they define the mass cut separating the ejecta from the part locked into compact objects. In Sect. 7 below we shall consider various possibilities related to black hole formation, but here we consider the case (case A) where all the onion skin layers of the pre–supernova model are ejected, with the exception of the remnants which we consider now. The residual baryon masses (which have to be considered rather than the neutron star masses) have been given for stars with initial masses between 10 and 25 $M_\odot$ at the time of supernova explosions by Wilson et al. (1986; cf. also Woosley 1986; Thielemann et al. 1992). It would be wrong to adopt as such these residual baryon masses in function of the initial masses, because our final stellar masses are very different due to mass loss (cf. Sect. 3). It is more meaningful to establish a relation between the residual baryon masses and the mass M_{CO} of the CO cores, since whatever the previous history and mass loss, it is likely that stars with a given M_{CO} at the end of the C–burning phase will leave the same kind of remnant. Table 4 gives the masses of the remnants obtained in this way. If different remnants are adopted (in the past many authors took 1.4 $M_\odot$ for any large enough masses), the chemical yields in heavy elements must then be modified accordingly (Tables 5 – 6 provide

Table 3. Contributions from the winds to the stellar yields (values in units of the solar mass)

Mass	He	C	O	N	Ne	Z
Z=0.001						
120	7.526	-0.005	-0.013	0.018	0	0
85	2.529	-0.002	-0.005	0.007		
60	0.725	-0.001	-0.002	0.003		
40	0.001	0	0	0		
25	0.001					
Z=0.020						
120	42.871	7.745	-0.128	0.661	1.114	9.392
85	17.049	13.125	3.371	0.308	0.869	17.751
60	13.787	6.890	1.032	0.249	0.508	8.688
40	6.507	4.513	1.458	0.170	0.253	6.395
25	0.941	-.022	-0.035	0.057	0	0
20	0.079	-.002	-0.002	0.004		
15	0.048	-.001	-0.002	0.003		
12	0.014	-.001	-0.001	0.002		
9	0.008	-.001	-0.000	0.001		
Z=0.020 lower $\dot{M}$						
120	19.651	19.796	8.375	0.472	1.195	29.973
85	6.897	13.245	9.907	0.266	0.727	24.318
60	8.025	7.279	3.339	0.230	0.404	11.281
40	4.522	2.940	2.022	0.163	0.158	5.295
25	0.336	-.007	-.010	0.017	0	0
20	0.025	-.001	-.001	0.002		

the necessary information if such changes are to be made). For intermediate mass stars, we have taken as remnant masses the mass M_{CO} of the CO cores. As discussed in Sect. 3, these masses agree generally well with the white dwarf masses obtained by Weidemann (1987 1990). Moreover, as shown by Table 4, there is a good continuity between these remnant masses and those derived from Woosley (1986) for higher masses. For stars which experience the He-flash (i.e. M$\leq 2\ M_{\odot}$), since the evolution has not been followed beyond this point, we take as remnant masses the WD masses given by Weidemann (1987), which thus ensures reliable estimates of the amount of helium synthesized.

Table 4. Remnant masses (in solar unit)

M	Z=.001	.020	.020 Lower $\dot{M}$
120	17.1 :	1.48	2.82
85	11.4 :	1.77	3.16
60	7.6 :	1.64	2.88
40	4.3 :	1.80	2.96
25	2.65	2.72	2.74
20	2.14	2.15	2.16
15	1.68	1.65	—
12	1.46	1.42	—
9	1.28	1.23	—
7	1.11	1.01	—
5	0.88	0.73	—

The derivation of the supernova yields in helium and heavy elements Z brings no problem, since the evolution is followed far enough for these quantities to be accurately determined from the distribution of chemicals in the models. The yields in Y and Z are given in Tables 5 and 6 for the two metallicities considered here.

Table 5. Stellar yields for models with $Z = 0.001$ (in solar mass units)

Mass	He	C	O	Z	He	C	O	Z
	Final Ejecta (SN, PN)				Wind and Final Ejecta			
120	2.28	0.89	35.30	41.6	9.81	0.88	35.3	41.6
85	5.56	0.72	22.60	26.7	8.09	0.72	22.6	26.7
60	5.23	0.70	14.20	17.1	5.96	0.70	14.2	17.1
40	4.24	0.55	6.80	9.71	4.24	0.55	6.80	9.71
25	3.52	0.403	2.40	4.45	3.52	0.403	2.40	4.45
20	2.11	0.298	1.27	2.93	2.11	0.298	1.27	2.93
15	1.65	0.196	0.46	1.53	1.65	0.196	0.46	1.53
12	1.35	0.101	0.15	0.83	1.35	0.101	0.15	0.83
9	0.98	0.056	0.004	0.27	0.98	0.056	0.004	0.27
7	0.788				0.788			
5	0.452				0.452			
4	0.285				0.285			
3	0.091				0.091			
2.5	0.065				0.065			
2	0.059				0.059			
1.7	0.026				0.026			
1.5	0.022				0.022			
1.25	0.016				0.017			
1	0.010				0.010			

For the stellar yields mp^{SN}_{Cm} in carbon from supernovae, we proceed as follows. The extensive pre–supernova models made in Meynet's thesis (1990) show that a part of the C–distribution existing in the CO core at the end of C–burning is entirely destroyed by further nuclear reactions, up to the supernova stage, while another part of this C–distribution remains unmodified during further evolution. Let us call f the fraction of M_{CO}, inside which carbon is destroyed during the late phases. From the models by Meynet we see that f is a very smooth function.

Thus we consider that the SN ejecta in carbon consist of the C–distribution in the star as it is at the end of the C–burning phase, but we only count the layers which are external to the mass $f \cdot M_{CO}$. In this way we are able to take into account the C–destruction which occurs in the CO core after the end of central C–burning. Moreover, we verify from the existing C–distributions that the exact value of f is not critical because most of the left–over carbon lies in the C–peak at the transition from He–rich to O–rich layers and this is generally well outside the mass $f \cdot M_{CO}$. The yields mp^{SN}_{Cm} in carbon are reliably obtained in this way and are given in solar mass units in Tables 5 and 6 for metallicities $Z = 0.001$ and 0.020.

For the yields mp^{SN}_{Om} in oxygen, the procedure is even simpler. The various pre–supernova models by Woosley & Weaver (1986), Meynet (1990), Thielemann et al. (1991) and Arnett (1991) show that there is a very well defined relation between the total amount of ^{16}O produced and the mass of the CO core. Here we are using the relation by Arnett (1991), which is the most extended one and is based on updated nuclear reaction rates. The yields mp^{SN}_{Om} are given in solar mass units in Tables 5 and 6. The

Table 6. Stellar yields for models with $Z = 0.020$ (in solar mass units)

Mass	He	C	O	Z	He	C	O	Z
	Final Ejecta (SN, PN)				Wind and Final Ejecta			
120	-0.128	0.290	0.18	0.72	42.74	8.04	0.05	10.11
85	-0.392	0.350	0.59	1.56	16.66	13.48	3.96	19.31
60	-0.263	0.333	0.40	1.16	13.52	7.22	1.43	9.85
40	-0.410	0.369	0.62	1.61	6.10	4.88	2.08	8.01
25	0.600	0.319	2.60	4.48	1.54	0.297	2.57	4.48
20	1.520	0.221	1.27	2.73	1.60	0.219	1.27	2.73
15	1.338	0.141	0.41	1.32	1.386	0.140	0.41	1.32
12	1.181	0.072	0.11	0.686	1.195	0.071	0.11	0.686
9	0.871	0.028	0.00	0.173	0.879	0.027	0.00	0.173
7	0.684				0.688			
5	0.401				0.403			
4	0.184				0.185			
3	0.072				0.074			
2.5	0.079				0.080			
2	0.066				0.067			
1.7	0.019				0.020			
1.5	0.015				0.016			
1.25	0.012				0.013			
1	0.010				0.012			
Case of lower $\dot{M}$								
120	-1.304	0.410	2.80	4.56	18.347	20.206	11.18	34.53
85	-1.654	0.393	3.65	5.60	5.243	13.638	13.56	29.92
60	-1.344	0.462	2.95	4.71	6.681	7.741	6.29	15.99
40	-1.406	0.483	3.15	4.91	3.116	3.423	5.17	10.20
25	1.330	0.266	2.55	4.50	1.666	0.259	2.54	4.50
20	1.560	0.233	1.27	2.82	1.585	0.232	1.27	2.82

physical reason for the reliability of the relation between the amount of ^{16}O produced and M_{CO} is that most of the CO cores consist of oxygen, and that there is no significant oxygen outside M_{CO}. Therefore, the fraction of oxygen which is preserved in the CO core depends in a one–to–one way on the mass M_{CO}. This procedure would not have been appropriate for carbon, because most of the surviving carbon at the time of the supernova is at the very edge and outside the CO core. Thus, there would be a large scatter in the carbon production vs. M_{CO}, depending very much on previous evolution, particularly in case of extreme mass loss. This would have made the carbon vs. M_{CO} relation rather uninteresting for our purpose and this is why we had to devise a more reliable procedure in this case.

Tables 5 and 6 give the various stellar yields, in terms of mp_{im}, the mass (in solar mass unit) of element i ejected by a star of initial mass m. The initial masses from 1 to 120 $M_\odot$ and metallicities $Z = 0.001$ and 0.020 are considered and the yields in helium, heavy elements Z as a whole, carbon and oxygen are given. The left part of the Tables provides the final ejecta, in supernovae SN or planetary nebulae PN, while the right part gives the sum of the wind and final ejecta.

6. Results on the stellar yields over the whole range of stellar masses

An overall representation of the stellar yields is necessary to allow us to analyse their main properties as a function of initial mass and Z. Figures 5 and 6 show the mass fractions p_{im} ejected in the form of various elements for the models with $Z = 0.001$ and 0.020. The wind contributions are shown by hatched areas to clearly distinguish them from the final ejecta, usually in supernovae or planetary nebulae. The upper empty part of the diagram corresponds to the original matter ejected without nuclear processing in the stars. The lower part of the diagram represents the mass fraction locked in the remnants, some indications on the possible kinds of supernova events and remnants are given (see Sect. 7 below). The comparison of these figures is enlightening. We may especially point out the following noticeable facts:

- For massive stars, the dominant effect is that of stellar winds, which influence both the yield in the wind and in the supernovae. At high Z, large amounts of He and C are ejected before being further processed to heavy elements; this results in large He and C stellar yields and in a drastic reduction of the production of heavy elements, particularly of oxygen. At $Z = 0.001$, the contributions of the winds are negligible. The stellar yields consist mainly of the final ejecta. Fig. 5 shows the huge yield in oxygen and the very small one in carbon, which is typical of the classical constant mass evolution.
- For low and intermediate mass stars, the stellar yields in helium are relatively smaller in higher Z models. The reason is the much thinner He–rich shell in higher Z models; also, in these models one has to substract a larger amount of initial helium.

On the whole, as shown by Figs. 5 and 6, *the nucleosynthesis of helium, carbon, oxygen, neon and heavy elements is a function strongly depending on both mass and Z*.

It is amazing to compare the present stellar yields as a function of initial masses to the results by Woosley & Weaver (1986) and by Arnett (1991). This is made in Figs. 7 to 10 for helium, carbon, oxygen and heavy elements Z. As expected, we notice that in general there is a very good agreement between the results of our model at $Z = 0.001$ and the constant mass evolution models by other authors (despite the difference of initial compositions). For helium (Fig. 7) the ejecta of the models at $Z = 0.02$ are much larger as mentioned above for massive stars which enter the WR stage, otherwise their yields in helium are reduced by mass loss (cf. Maeder 1981). For carbon (Fig. 8) the very high wind of WC stars contributes to a large injection of ^{12}C into the interstellar medium. We notice that the yields in ^{12}C by Arnett (1991) are larger than the corresponding ones by Woosley & Weaver (1986) or ours; not enough information about Arnett's model is available to trace back this difference. For oxygen (Fig. 9) we notice the enormous reduction of our yields at $Z = 0.020$ compared to those of other models. As a matter of fact, such a difference has great impact on the chemical evolution of galaxies. For Z (cf. Fig. 10), the contributions of our models of massive stars at $Z = 0.020$ are not as low as is the case for oxygen, the balance being due to the large injection of carbon by the winds of massive stars.

The stellar yields of Tables 5 and 6 have to be properly weighted by the IMF (Initial Mass Function). There are various recent studies and representations of the IMF; also, the possibilities of bimodal star formation or of top–heavy IMF in case of starbursts have been considered (cf. Scalo 1986, 1987). Figs. 11 and 12 show, for $Z = 0.001$ and 0.020, the product functions

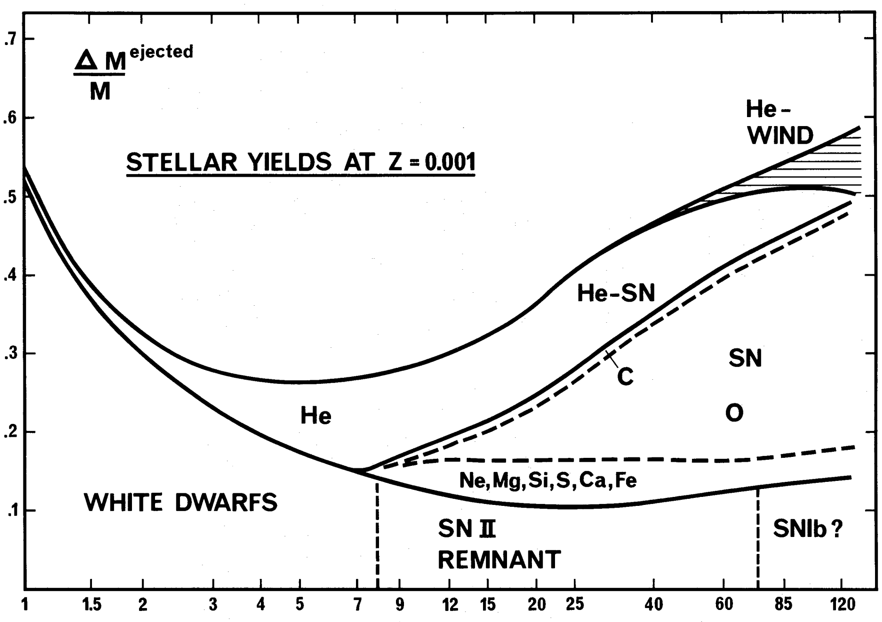

Fig. 5. Stellar yields or mass fractions ejected as a function of the initial masses for metallicity $Z = 0.001$. The quantities shown are the mass fractions p_{im}. The wind contribution is indicated by hatched areas. Some indications on the composition of the ejecta are given. The lower part represents the mass fraction in the remnants

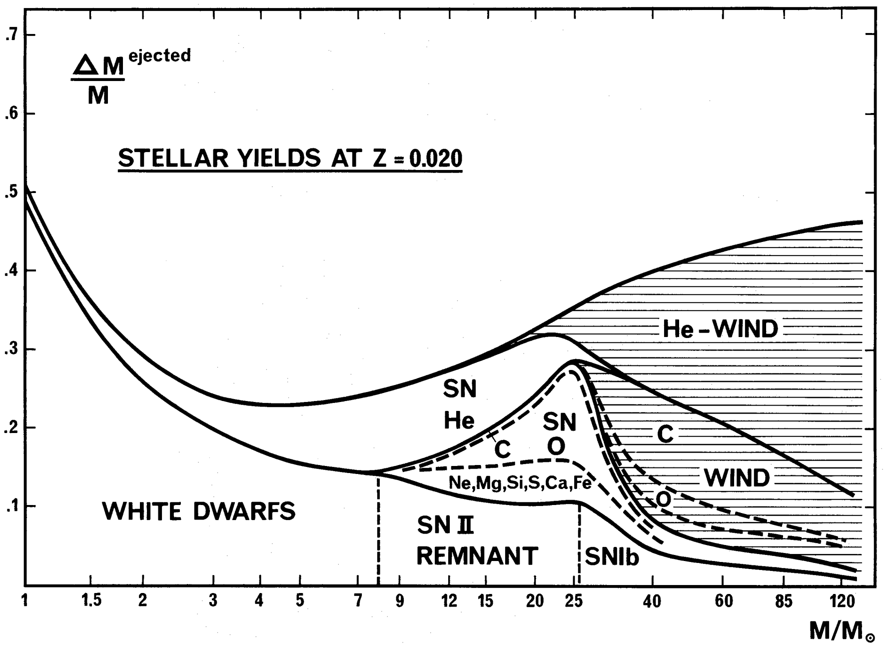

Fig. 6. Same as Fig. 5 for $Z = 0.020$

$$mp_{im}\,\frac{dN}{dM}$$

where dN/dM expresses the IMF, which is taken in the examples below as a power law $dN/dM = M^{-(1+x)}$ with x = 1.35, i.e. the classical standard Salpeter's mass function. The data of Tables 5 and 6 enable the reader to try, if useful, other cases of IMFs. The net yields below are also calculated for an IMF slope $x = 1.7$, which is preferable according to Scalo (1986). We notice the following points:

Overall helium and Z productions:

- With the weighting of a standard IMF, the mode for helium production is around 4–5 $M_{\odot}$ for all metallicities.
- The median masses for helium production are about 11 and 16 $M_{\odot}$ for models at $Z = 0.001$ and 0.020 respectively (the interval 1 to 120 $M_{\odot}$ being considered).
- The helium curves in Fig.11 demonstrate that at low Z small masses contribute more to the enrichment in helium, while at high Z the contribution of large masses is relatively more important.
- The mode for the Z–production is at 17 $M_{\odot}$ for $Z = 0.001$ and at 19 $M_{\odot}$ for $Z = 0.020$.
- The median masses are 42 and 34 $M_{\odot}$ for $Z = 0.001$ and 0.020. Thus we see that at low Z the difference of the median masses for He and Z production is important.

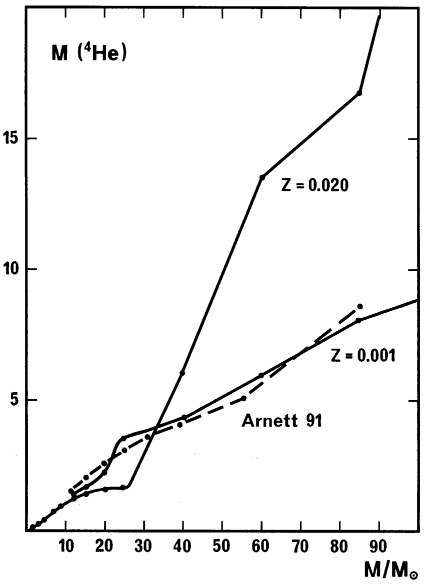

Fig. 7. Amount of helium produced (in units of solar mass) as a function of the initial stellar masses and for two metallicities. The values by Arnett (1991) are also indicated

7. The net yields as a function of Z and M_{BH} in relation with chemical evolution of galaxies

Let us now examine some of the main consequences of the present stellar models and their nucleosynthesis for the chemical evolution of galaxies; nevertheless we do not enter the construction of models for galactic chemical evolution, which are beyond the scope of this paper.

7.1. The mass limit for black hole formation

The chemical yields are not independent of the conditions for black hole formation. It is essential to know the lowest initial mass limit M_{BH} (or alternatively the lowest M_{CO}) leading to black hole formation. Particularly relevant for the yields is the question of what fraction of the onion skin model is swallowed by the black hole at the time of core collapse. If all is swallowed, the yields of massive stars will only consist of the stellar winds previously ejected. The various situations which may occur can strongly change the estimated yields.

The birth of neutron stars has been studied by Burrows & Lattimer (1986; see also Burrows 1987, 1988). Black hole candidates such as Cygnus X–1 and A0620–00 possibly result from stars with helium cores in the range of 10–15 $M_\odot$ (cf. Burrows 1992). According to this author, if after the bounce at nuclear densities the core is too large ($M \geq 2\ M_\odot$) to explode by neutrinos or direct shock, the massive transient neutron star experiences accretion for a few seconds before collapsing by general relativistic instability within less than 1 ms (cf. also Burrows 1987). The rest of the star is then accreted into the new black hole through a transient massive disk, so that little mass should be lost subsequently to the general relativistic collapse and that no supernova should accompany this event.

The theoretical context is still very uncertain and we shall consider, in view of the above possible scenario, several different cases noted A, B, C, D, E. These cases encompass a wide range of possibilities:

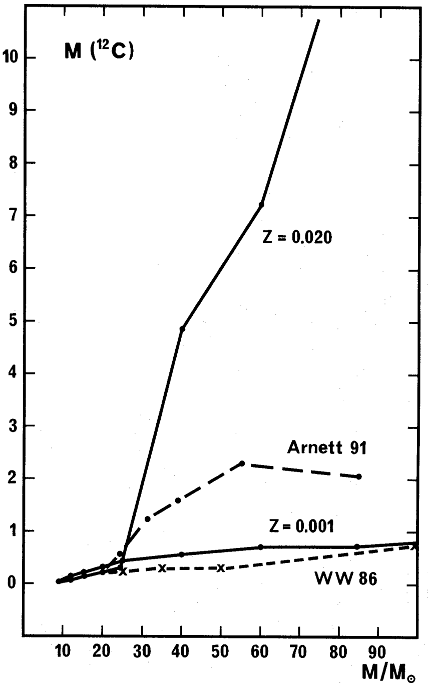

Fig. 8. Amount of carbon produced. Same remarks as for Fig. 7. The values by Arnett (1991) and Woosley & Weaver (1986) are also indicated

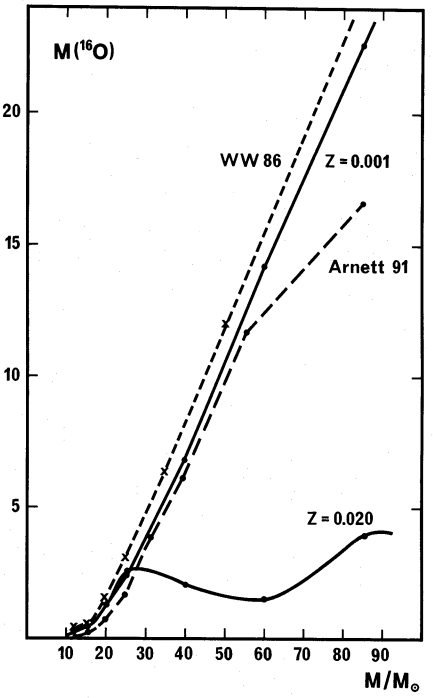

Fig. 9. Amount of oxygen produced. Same remarks as for Fig. 8

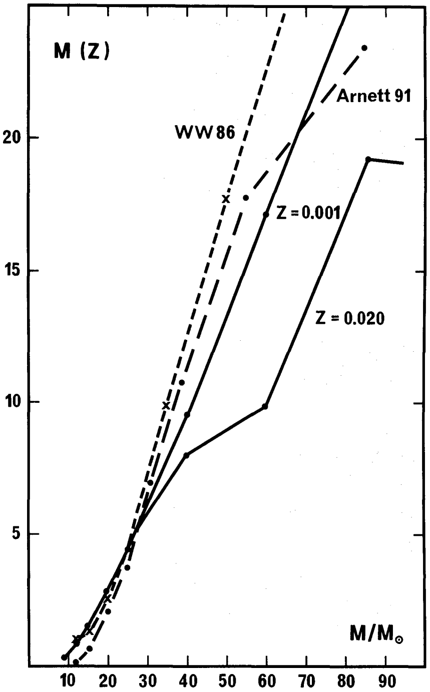

Fig. 10. Amount of heavy elements produced. Same remarks as for Fig. 8

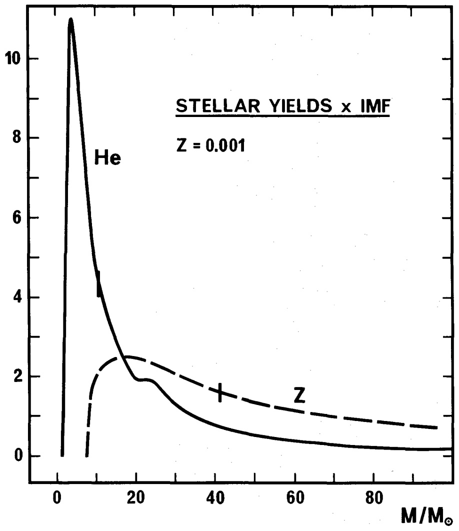

Fig. 11. Products of the stellar yields in helium and heavy elements by the IMF (slope $x = 1.35$) for models with initial metallicity $Z = 0.001$

A In this case we assume that in the presuvernova model all the onion skin layers surrounding the remnant (cf. Sect. 5) are ejected. This is the assumption usually made in literaure (cf. for example Arnett 1978, 1991; Maeder 1981; Woosley 1986).

B In this case we assume that the entire star remaining at the time of core collapse is swallowed by the central object if the mass of the CO core is larger than $M_{CO} = 8\ M_{\odot}$. This corresponds to $M_{\alpha} = 10.6\ M_{\odot}$ and for $Z = 0.001$ (cf. Table 2) to a lowest mass for black hole formation $M_{BH} = 27.5\ M_{\odot}$. For $Z = 0.020$ the limit $M_{CO} = 8\ M_{\odot}$ is never reached (cf. Fig. 3), thus this case is identical to case A.

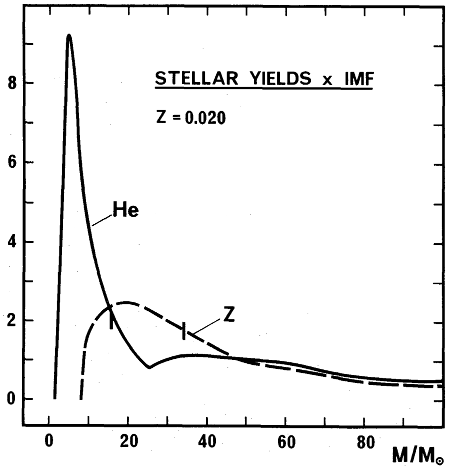

Fig. 12. Same as Fig. 11 for $Z = 0.020$

C This case is the same as case B, except for a limit at $M_{CO} = 6\ M_{\odot}$ and $M_{BH} = 22.5\ M_{\odot}$ for any metallicity.

D Same as B, for $M_{CO} = 4\ M_{\odot}$ and $M_{BH} = 17.5\ M_{\odot}$.

E Same as B, for $M_{CO} = 2\ M_{\odot}$ and $M_{BH} = 11.6\ M_{\odot}$.

We may roughly estimate the mass of the neutron stars corresponding to the various cases above by using the table given by Woosley (1986), based on calculations by Wilson. There is certainly still a lot of uncertain physics in such a correspondence, but it may help to fix ideas. From Woosley's data, the masses of the neutron stars corresponding to cases B, C, D, E would be about 2.4 $M_{\odot}$ (extrapolated), 2 $M_{\odot}$, 1.6 $M_{\odot}$ and 1.3 $M_{\odot}$. The corresponding values from models by Thielemann et al. (1992) appear to be somehow lower, in the range of 1.7 to 1.3 $M_{\odot}$ for models with delayed shock mechanism. The corresponding values of the baryon masses are of course larger, typically by about 0.2 $M_{\odot}$. In cases C and D, large enough initial masses at $Z = 0.020$ may lead to M_{CO} values lower than the adopted limits (cf. Fig. 3). When this occurs, of course we do not assume black hole formation and swallowing. This also means that very large initial masses may again lead to the formation of neutron stars, black holes only forming in an intermediate range of masses, between 22 and 30 $M_{\odot}$ for case C, and between 17 and 40 $M_{\odot}$ for case D.

7.2. Values of the net yields in heavy elements and comparison with observations

Table 7 gives the net yields in helium, heavy elements Z, oxygen, carbon and the returned fraction R for $Z = 0.001$ and 0.020, for the cases A, B, C, D, E defined above and for the IMF slope $x = 1.7$ (cf. Scalo 1986) integrated between 1 and 120 $M_{\odot}$. Table 8 gives some complementary data for another IMF slope (Salpeter's value $x = 1.35$) and for the case with lower mass loss rates $\dot{M}$ for stars with $M \geq 20\ M_{\odot}$ (cf. Sect. 2). The returned fraction R is, as expected, larger at larger Z, more mass being ejected by stellar winds and the remnants being smaller. Also we notice that R decreases when there are more black holes formed (from A to E). Indeed (1-R) corresponds to the average fraction locked into the remnants. A change from $x = 1.7$ to 1.35 gives more weight to massive stars and thus increases R.

As shown in Table 7, the net yield in helium is larger at higher Z. This is due to the larger helium ejection by the wind of massive stars at $Z = 0.020$, which is not compensated by the slightly lower helium production by the intermediate mass stars. We notice that the yield in helium is not very much reduced by a decrease of the lowest mass M_{BH} for black hole formation (from A to E). This is quite normal, since most helium is ejected by low and intermediate mass stars or by the winds of massive stars. This effect has important consequences for the $\Delta Y/\Delta Z$ ratio. The explanation for the changes with the IMF slope or with the $\dot{M}$-rate follows the same line of arguments.

The yields in oxygen and heavy elements Z strongly decrease with the lowering of M_{BH} from 120 $M_{\odot}$ to 11.6 $M_{\odot}$ (A to E), since then more heavy elements are swallowed by black holes (cf. also Schild & Maeder 1985). The decrease is however less important at $Z = 0.020$, because in this case a large fraction of the heavy elements is anyway ejected in the winds and escapes. As shown by Table 7 for $Z = 0.020$, this is particularly the case for carbon, for which the yields (from winds) are quite large and show no great variations with M_{BH}. This occurs also for the case with lower $\dot{M}$-rates, since even in this case the winds are strong enough to eject significant amounts of carbon. However, at $Z = 0.001$, the carbon yields behave like those of the other heavy elements. The main result of this discussion is that *the yields y_Z, y_O, y_C are not constant during galactic evolution as generally assumed, but are highly variable with metallicity, increasing or decreasing in a way which depends on the lowest limit M_{BH} for black hole formation.*

Table 7. Net yields y in helium, carbon, oxygen and heavy elements. Returned fraction R. IMF: $x = 1.7$.

Case	He	Z	O	C	R
Z=0.001					
A	0.1865	0.1053	0.06410	0.00820	0.7137
B	0.1400	0.0367	0.01352	0.00453	0.6636
C	0.1284	0.0275	0.00861	0.00363	0.6497
D	0.1143	0.0173	0.00414	0.00249	0.6294
E	0.0868	0.0042	0.00038	0.00076	0.5815
Z=0.020					
A	0.2001	0.0928	0.02919	0.03328	0.7423
B	idem	idem	idem	idem	idem
C	0.1927	0.0772	0.02109	0.03131	0.7350
D	0.1757	0.0570	0.01222	0.02810	0.7192
E	0.1444	0.0352	0.00598	0.02300	0.6863

Table 8. Complementary tables on the net yields for different slopes x of the IMF and mass loss rates

Case	He	Z	O	C	R
Z=0.001, x=1.35					
A	0.2867	0.2604	0.17166	0.01765	0.7614
B	0.1539	0.0549	0.02126	0.00662	0.6470
C	0.1364	0.0383	0.01257	0.00497	0.6219
D	0.1121	0.0222	0.00550	0.00316	0.5882
E	0.0775	0.0047	0.00044	0.00084	0.5182
Z=0.020, x=1.35					
A	0.3540	0.2278	0.09407	0.06872	0.7930
B	idem	idem	idem	idem	idem
C	0.3285	0.1854	0.08645	0.04863	0.7798
D	0.2812	0.1337	0.02784	0.07405	0.7529
E	0.2154	0.0833	0.00141	0.05761	0.7042
Z=0.020, x=1.70 lower $\dot{M}$					
A	0.1801	0.1146	0.04890	0.03189	0.7408
B	0.1785	0.0996	0.03977	0.03018	0.7371
C	0.1693	0.0716	0.02439	0.02686	0.7221
D	0.1489	0.0564	0.01790	0.02444	0.7050
E	0.1181	0.0383	0.01244	0.02048	0.6674

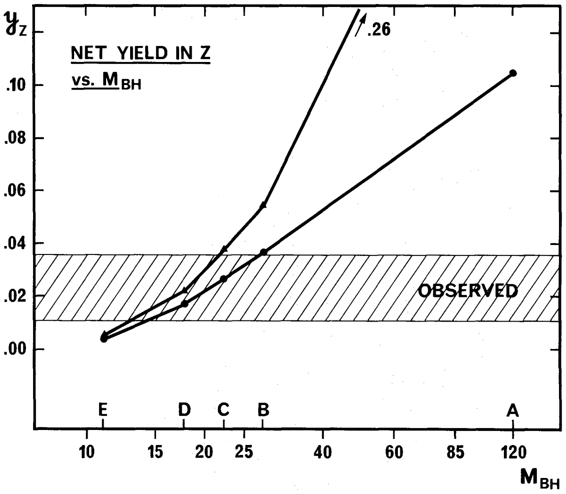

Fig. 13. Values of the net yields in heavy elements as a function of different values of M_{BH}. Cases A, B, C, D and E are indicated. Two values of the slope x of the IMF are considered: $x = 1.70$ (dots) and $x = 1.35$ (triangles). The models for $Z = 0.001$ are represented here. Tables 7 and 8 give additional data. The range of observed values is indicated by hatchings (see text)

It is interesting to compare our theoretical yields from stellar nucleosynthesis to values derived from constraints coming from chemical evolution of galaxies. Pagel (1987) has given estimates of the yields y_Z in a variety of astrophysical sites: globular clusters in the halo, globular clusters in the disk, the solar neighbourhood and the galactic bulge. Pagel suggests that the highest value $y_Z = 1.8\ Z_{\odot}$ which he finds for the galactic bulge could represent some kind of a "universal true yield", and that the lower yields found in other cases may be due to loss of enriched gas in galactic winds. Edmunds (1989) has shown how significantly the apparent yield could be modified by gas inflow or outflow. Alternative possibilities considered by Pagel are that the differences in the yields for different sites may result from variable IMF or that the high yield for the galactic bulge may be due to inflow of processed material, a possibility which he holds for less likely. Other estimates of the yields have been made by other authors. For example, Rana (1992) finds a value $y_Z = 0.55\ Z_{\odot}$ on the basis of the metallicity distribution of stars in the solar neighbourhood, in general agreement with Pagel.

On the basis of the previous discussion, we may consider that the "observed yield" in heavy elements is likely but with several uncertainties in the range $y_Z = 0.01$ to 0.036. This range is compared to theoretical curves in Fig. 13 (see also Tables 7 and 8). From these comparisons, the first very clear conclusion is that *case A (all onion skin layers ejected for all masses) appears to be excluded by a very wide margin, whether the slope x of the IMF is 1.35 or 1.7 or whether models at $Z = 0.001$ or 0.020 with different mass loss rates are considered.* The other cases B to E ($M_{BH} = 27.5\ M_\odot$ to $11.6\ M_\odot$) clearly seem to lead to values more compatible with the observed range, although the exact choice would depend on Z and IMF slope x. This means that black holes are likely to swallow what is left from the onion skin models, after the escape of stellar winds, down to M_{BH} around at least $20 - 25\ M_\odot$. (Interesting enough, if we would have taken remnant masses equal to $1.4\ M_\odot$ for all initial masses rather than values based on Woosley's data (cf. Sect. 5), we would have found the net yields for case A even in larger disagreement with the observations. This clearly supports the rejection of case A).

The comparison may also be based on the yields in oxygen. The oxygen abundance is often the observed quantity, for example in HII regions and blue compact galaxies (cf. Lequeux et al. 1979), while Z is derived by assuming an O/Z ratio. Josey & Tayler (1991) estimate the yield y_O on the basis of the distribution of the oxygen abundances in G–dwarfs by Pagel (1989a) and find a value y_O equal to 0.8 of the present oxygen abundance. If the infalling gas has non–zero oxygen abundance, the yield could be reduced to half of the above value. With a present $Z = 0.02 - 0.03$ and a ratio $O/Z \simeq 0.53$ (cf. Anders & Grevesse 1989), we thus have $y_O = 0.008 - 0.013$ as the most probable range, with a possibility to have it down to $y_O = 0.004$. The comparison is made in Fig. 14 (see also Tables 7 and 9). Again, whatever metallicity and slope of the IMF are considered, case A with all onion skin layers ejected, appears to be out of the range by a sizeable margin. From Table 7, the range C–D, i.e. with M_{BH} around $20\ M_\odot$, appears to be the most likely one, whether model $Z = 0.001$ or $Z = 0.020$ is considered.

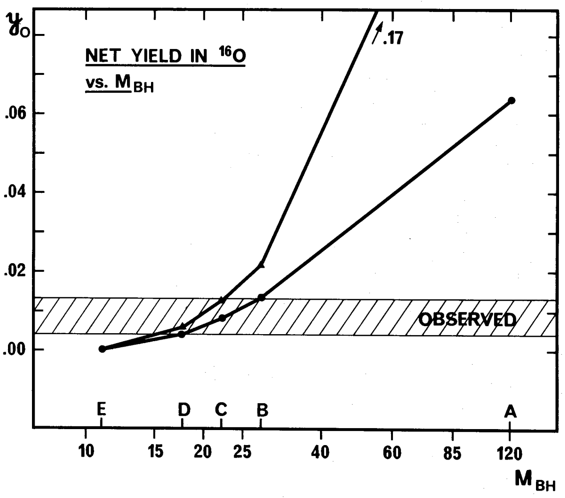

Fig. 14. Same as Fig. 13 for the net yields in oxygen

Finally, we notice as a marginal remark that for models B–E the metal yields are increasing with metallicity Z, in agreement with the analysis by Peimbert & Serrano (1982). On the contrary, for models A there would be no increase of the yields y_Z with metallicity. However, this must not be taken as an argument for cases B to E, since inflows or outflows may also alter the observed yields, as shown by Pagel (1987) and Edmunds (1989).

7.3. The $\Delta Y/\Delta Z$ ratio

The ratios $(\Delta Y/\Delta O)$ and $(\Delta Y/\Delta Z)$ of the relative helium to oxygen or metal enrichments are parameters of major importance for galactic chemical evolution and cosmology. These ratios critically influence the estimate of the primordial helium originated from big bang nucleosynthesis (for recent references, see Pagel 1987, 1989a, 1992; Pagel et al. 1992; Audouze 1987; Olive et al. 1990; Steigmann et al. 1991). Helium is generally best determined from extragalactic HII regions, which span a wide range of metallicities and therefore allow the determination of the helium content near zero metallicity. HII regions have been extensively analysed in order to determine the abundance of primordial helium (e.g. Peimbert & Torres Peimbert 1974; Lequeux et al. 1979; Kunth & Sargent 1983; Kunth 1983; Pagel et al. 1986; Peimbert 1986; Pagel 1989ab, 1992; Pagel et al. 1992).

Simple models of galactic chemical evolution (cf. Peimbert & Torres Peimbert 1974) lead to a linear relation between Y and Z, the helium and metal contents in a galaxy:

$$Y = Y_p + (\frac{\Delta Y}{\Delta Z}) \cdot Z$$

As a matter of fact, Z cannot be measured directly. The observations of heavy elements rest on ^{16}O, the most abundant element, the abundance of which can rather reliably be determined in HII regions. Thus, correlations are generally made between the observed Y and the (O/H) ratio for HII regions (or with N/H, cf. Pagel et al. 1992). The primordial He/H ratio (or Y_p in mass fraction) is thus obtained by a linear extrapolation of the Y vs. O/H plot to zero O/H. If the considered plot is Y vs. Z, some estimates $Z(^{16}\mathrm{O})$ of the metal content are usually made on the basis of the observed abundances of oxygen and other heavy elements.

The recent detailed analyses by Pagel et al. (1992) of low metallicity extragalactic HII regions led them to conclude that their preferred value for the $\Delta Y/\Delta Z$ ratio is in the range 4 to 5, certainly above 3 and possibly up to 6. This confirms previous values by Pagel et al. (1986) or by Peimbert (1986) who derived $\Delta Y/\Delta Z \simeq 3.5$. This value is also relatively consistent with the value of 3 found by Lequeux et al. (1979). Also, we have pointed out in Sect. 2 above that present solar Y and Z contents favour a $\Delta Y/\Delta Z$ ratio equal to or larger than 3. Kunth & Sargent (1983) found a value around 1, but a possible explanation of their result is given by Pagel et al. (1992). Thus, here we retain $\Delta Y/\Delta Z$ in the range 3 – 6, with a preferred value between 4 and 5 at low metallicity.

Table 9 shows the theoretical values of $\Delta Y/\Delta Z$ (as shown in Sect. 4 above, this is just the ratio of the respective yields in simple models). For case A with no black holes, we find values in the range of 1 to 2. Let us recall that Arnett's models (1978) lead to $\Delta Y/\Delta Z = 0.73$. As well known, these values are too small with respect to the observed ones. The hope was (cf. Maeder 1981) that stellar winds with their very high yields in helium could lead to sufficiently high $\Delta Y/\Delta Z$. However from Table 9 we see that this fails whatever metallicity or slope of the IMF considered. The swallowing of the onion skin layers by black holes enhances the $\Delta Y/\Delta Z$ ratio (cf. Schild & Maeder, 1985), since mostly heavy elements are trapped into the remnants. Table 9 (cf. also Fig. 15) shows that case C (with M_{BH} at $22.5\ M_\odot$) leads to $\Delta Y/\Delta Z = 4.7$ for low metallicity regions and $x = 1.7$, in best agreement with observations. This gives a good support to a minimum mass for black hole formation in the range of 20–25 $M_\odot$.

Table 9. Relative enrichments $\Delta Y/\Delta Z$ of helium to heavy elements for different metallicities Z and slopes x of the IMF

Case	x=1.70	x=1.35
Z = 0.001		
A	1.77	1.10
B	3.81	2.80
C	4.67	3.56
D	6.61	5.05
E	20.67	16.49
Z = 0.020		
A	2.16	1.55
B	2.16	1.55
C	2.50	1.77
D	3.08	2.10
E	4.10	2.59

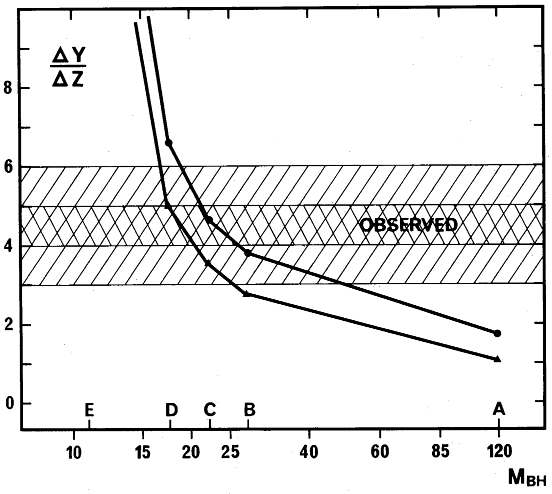

Fig. 15. Values of the ratio $\Delta Y/\Delta Z$ of the relative helium–to–metal enrichments as a function of M_{BH}. Cases A, B, C, D and E are indicated. Models for $Z = 0.001$ with IMF slope $x = 1.35$ (triangles) and $x = 1.70$ (dots). The observed range (cf. Pagel et al. 1992) is indicated by hatchings, the range 4 to 5 is the preferred one.

Shifting the IMF slope to $x = 1.35$ does not significantly modify the conclusions. Interestingly enough, while for case A an increase of the winds leads to higher $\Delta Y/\Delta Z$ ratios for the reasons explained above, the opposite occurs for cases B to E, where the $\Delta Y/\Delta Z$ ratios are slightly smaller at $Z = 0.02$ than at $Z = 0.001$. This results from the fact that at $Z = 0.02$ the heavy winds are carrying away a lot of heavy elements, and that the amount of heavy elements swallowed by black holes is not as large as in the case $Z = 0.001$. A value of $\Delta Y/\Delta Z = 3$ at $Z = 0.02$ is obtained by a model in the range C–D ($M_{BH} = 17.5 - 22.5\ M_\odot$). This can be brought into relation with the remark by Pagel et al. (1992) that if a $\Delta Y/\Delta Z$ ratio of about 3 could apply around solar metallicity, an increase of this ratio towards low metallicity is quite possible. It is interesting to notice that Table 9 reflects this trend well.

Thus, after a long period of disagreement between theoretical and observed values, we can say that stellar nucleosynthesis is able to reproduce the observed $\Delta Y/\Delta Z$ if there are black holes formed for M_{CO} larger than 6 $M_\odot$, or for initial masses larger than about 20–25 $M_\odot$.

7.4. *The oxygen overproduction and the O/C ratio during galactic evolution*

Several authors (cf. Twarog & Wheeler 1982, 1987; Larson 1986; Matteucci 1986b; Olive et al. 1987; Wheeler et al. 1989) have shown that with the best current estimates of the yields, IMF and SFR, the theory of galactic chemical evolution leads to a large overproduction of oxygen with respect to the observed abundance. The typical overproduction amounts to a factor 2.6 (cf. Matteucci 1986b). Some authors have proposed various manipulations of the IMF, of the upper and lower mass limits, etc. ... to solve the problem. However, as emphasized by Wheeler et al. (1989), the problem of the overproduction of oxygen is exacerbated if one simultaneously wants to account for the large O/Fe abundance ratios in halo stars: even more severe "actions" on the IMF and SFR are then required in the modellisations. The situation is so critical that Twarog & Wheeler (1987) wonder whether the current stellar nucleosynthesis theory is able to provide reliable constraints on stellar evolution, IMF, SFR, or models of galactic chemical evolution.

From Table 7 we notice that the classical oxygen yield with no mass loss and no black hole swallowing is relatively high (case A at $Z = 0.001$; $y_O = 0.064$). This high oxygen yield is reduced by both the increase of the mass loss and the lowering of the minimum mass M_{BH} for black hole formation. Thus, models B–D in Table 7 offer a satisfactory solution of the problem emphasized by Twarog & Wheeler (1987). Other values of the IMF slope or of the mass loss rates (cf. Table 8) do not change this conclusion.

The O/C ratio for stars in the Milky Way keeps about constant with $X(O)/X(C) \simeq 2.3$ down to $[Fe/H] \simeq -2.0$ (cf. Wheeler et al. 1989), which corresponds to $Z < 0.001$. We may notice that model A at $Z = 0.001$ gives a much too large ratio, i.e. $X(O)/X(C) = 7.8$ or 9.7, depending on which IMF slope is chosen, while model C gives a correct ratio in the range 2.4 or 2.5. As the mass loss rates increase, the integrated O/C ratio slightly decreases. At $Z = 0.02$ for the case of lower $\dot{M}$–rates, the $X(O)/X(C)$ ratios are 0.9 to 1.9, while for the larger $\dot{M}$–rates it is 0.7 to 1.8 (case C being always considered). This discussion is only indicative because, as emphasized by Wheeler et al. (1989), the carbon abundance is subject to many uncertainties and also because complete models of galactic evolution are needed in this context.

7.5. *Supernovae SNIb and their number ratio to SNII*

The present models have some implications on the relative number frequencies of supernovae originating from WR stars with respect to supernovae SNII. Some correspondence between WR stars and the precursors of SNIb has been made (cf. Wheeler & Levreault, 1985; Ensman & Woosley,1988); however this correspondence has remained rather controversial. The main difficulty was that the final WR masses were generally too high to possibly account for SNIb. As pointed out by several authors (cf. Wheeler & Levreault 1985; Ensman & Woosley 1988; see also Nomoto et al. 1991), the light curves of SNIb can only be explained by precursors being low mass helium stars in the range of $3 - 7\ M_\odot$ depending on the author. As emphasized by Langer (1989; cf. also Langer et al. 1991), if the mass loss rates of WR stars depend on their actual masses, the resulting final WR masses are small enough to be in the range required for explaining SNIb. The present models confirm such small WR final masses in the range of 3 to 8 $M_\odot$ for models at $Z = 0.02$ and thus support the view that WR stars may be progenitors of SNIb supernovae.

Figs. 1, 5 and 6 show that the number of stars which finish their life as a low mass helium star is highly Z–dependent. At $Z = 0.02$, the lowest mass limit for forming WR stars is about 25 $M_\odot$ and most WR stars (except those originating from stars close to the mass limit, cf. Fig. 1) finish their life as low mass stars. This makes plenty of candidates for SNIb progenitors. At $Z = 0.001$, the expectation for WR stars to originate from single stars are so low (unless there is a so–called top–heavy IMF) that there should be almost no SN from WR stars.

The discussion above suggests that the relative number of SNIb with respect to other supernovae should increase with metallicity for similar IMF. Also, we notice (cf. Figs. 5 and 6) that the upper initial mass limit for SNII may decrease with increasing Z, while the lowest mass limit apparently does not change very much (cf. Matteucci & Tornambe, 1985). Thus, this may contribute to make the SNIb/SNII number ratio a strongly increasing function of metallicity, if SNIb mainly originate from WR stars.

8. Conclusions

The main results of this work are given in the abstract and are not repeated here. The final point is a word of caution. A model is some tool which from initial assumptions and physical ingredients predicts some logical consequences. We have used here recent and reasonable model assumptions and examined their effects on chemical evolution. Among important assumptions in this work we may mention those about the mass loss rates, their dependence on metallicity, and their dependence on the stellar masses for WR stars. Undoubtedly, these assumptions are backed up by several observational constraints and the trend of their general nucleosynthetic consequences are reliable; however some details of the parametrizations of mass loss effects may still be improved in the future.

We can also make a few additional remarks:

- The fact that the yields in heavy elements and oxygen vary with metallicity and are generally low, due to the possible swallowing up by black holes, may lead to a revision of past estimates of the SFR, of the IMF slope or of lower mass cuts in the IMF, which were based on the previous theoretical yields. In particular, the present yields may lead to an increase in the estimates of past star formation rates.
- The predicted number of black holes remains relatively small for usual IMF. If we consider that black holes form from stars with an initial mass in the range 20 to 120 $M_\odot$ (at $Z = 0.001$), and neutron stars from the range 8 to 20 $M_\odot$, this makes a number ratio of black holes to neutron stars equal to 25% or 37% for a slope x of the IMF equal to $x = 1.7$ or 1.35 respectively. However, if there had been top–heavy IMF in the past, for example in starburst galaxies, the number of black holes formed in earlier epochs could be higher. For $Z = 0.02$, we recall that black holes may probably only originate from a limited intermediate range of initial stellar masses (cf. §7.1), since very large initial masses end up with small final masses and may thus lead to neutron stars.
- We may also notice that our preferred case, i.e. case C with $M_{BH} = 22.5\ M_\odot$, corresponds to a mass of the oxygen core $M_{CO} = 6\ M_\odot$ (see also Fig. 3). This in turn corresponds to some value of the limiting neutron star mass. If we adopt the relation presented by Woosley (1986) based on calculations by Wilson, the corresponding limiting neutron star mass would be about 1.96 $M_\odot$. The study of neutron star masses by Thielemann et al. (1992) suggests that stars with initial masses in the range of 20 to 25 $M_\odot$ lead to neutron stars with masses in the range of 1.48 to 1.67 $M_\odot$ in case of delayed explosion. Thus, we emphasize that a value of M_{BH} in the range of 20–25 $M_\odot$ implies that neutron stars may form with masses up to about 1.5 (in the scale by Thieleman et al.) or 2 $M_\odot$ (in the scale by Woosley), a value which is consistent with current estimates of the maximum mass of neutron stars (cf. Burrows 1987).

Acknowledgements. I express my warmest thanks to Dr. G. Meynet, to Prof. A. Burrows, to Prof. J. Truran, to Dr. G. Schaller and Mr. D. Schaerer for much helpful information, and to Prof. J.C. Wheeler for very encouraging comments.

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