Massive stars and galactic evolution

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Abstract

The evolution and nucleosynthesis in massive stars are briefly reviewed, and compared with the information derived from SN1987A in LMC . Most of the theoretical models agree with the measured abundances and they can be used in models of galactic evolution.

Models of chemical evolution of galaxies are presented and the role of massive stars in their evolution is discussed.

Finally, the role of Wolf-Rayet stars in galactic evolution is studied, particularly from the point of view of their final fate. It is shown that, if Wolf-Rayet were the progenitors of type Ib supernovae, the Galactic chemical evolution would not change substantially with respect to the case of white dwarfs being the progenitors of type Ib supernovae. However, the predicted frequency of type Ib supernovae in the Wolf- Rayet case would be far too low in comparison with observational estimates.

I.Introduction

Massive stars play a major role in Astrophysics. They are responsible for the nucleosynthesis of the majority of heavy elements and, due to their short lifetimes (several 10^6 years), they dominate the chemical enrichment in the early phases of galactic evolution.

In order to understand the history of chemical enrichment in galaxies one has to know how stars evolve through the nucleosynthetic processes occurring in their interiors and how they restore the newly created and unprocessed material into the interstellar medium (ISM).

As is well known, the life of a star can be described as a sequence of nuclear burnings (H, He, C, Ne, O and Si) occurring in its central core. In stars massive enough ($M \geq 10-12 M_{\odot}$) all six nuclear burnings take place. This sequence stops with the formation of ^{56}Fe nuclei, after which the collapse of the Fe-core follows.

There are still many uncertainties and open problems in understanding the supernova explosion mechanism in massive stars. Two are the suggested mechanisms: a) prompt and b) delayed explosion. They are related to the shock originating from core bounce or neutrino heating, respectively. In case a) there are problems in causing a succesful explosion, whereas in case b) in reproducing the correct supernova energy (see Woosley, 1986; Hillebrandt 1987 for exhaustive reviews on this subject). In any case, the result of this explosion should be a supernova (SN) of type II.

When the shock wave passes through the stellar mantle, during SN explosion, explosive burnings occur (Si, O, Ne, C, He and H) and a considerable modification can be experienced by Si-Ca elements. All the ejected Fe-group nuclei in type II SNe are practically produced during explosive Si-burning. Recent hydrostatic and explosive nucleosynthesis calculations for massive stars are due to Woosley and Weaver (1986) (hereafter WW), Woosley et al. (1988) (hereafter WPW), Hashimoto et al. (1989), Thielemann et al.(1990) (hereafter THN), Arnett (1990). Most of these works were triggered by the occurrence of SN1987A in the LMC, which represents an optimal observational counterpart for nucleosynthetic models of a $20 M_{\odot}$ star (e.g. the estimated mass for SK-69202, the progenitor of SN1987A).

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Wolf-Rayet Stars and Interrelations with Other Massive Stars in Galaxies, 625–637.

Most of the nuclearly processed material in massive stars is ejected into the ISM during SNII explosion, although these stars loose mass also in a quiescent way (stellar winds) during H- and He-burning phases. The relative importance of the yields of He and metals from type II SNe and stellar winds has been studied in detail by Maeder (1981, 1983, 1985).

As illustrated in Fig. 1, the wind contribution to He becomes dominating with respect to the contribution to He from SNe only for stars with initial masses larger than $\simeq 60 M_{\odot}$, whereas the wind contribution to metals is always negligible with respect to the contribution of SNe, although stars with mass larger than $40 - 50 M_{\odot}$ can loose heavy elements in the wind. The observational counterpart of stars providing such a contribution is likely to be Wolf-Rayet (WR) stars of type WC.

On the other hand, heavy mass loss by stellar winds can affect the amount of metals ejected through a SN explosion. The main effect of a heavy mass loss is, in fact, to reduce the amount of metals which are ejected in SN explosion. In this case, the fact that much He is lost through the wind and not tranformed into heavier elements, contributes to a large reduction of the metal yields (see Maeder, 1990). Usually, in models of chemical evolution of galaxies the occurrence of mass loss in massive stars is taken into account by changing the relation between initial stellar mass, M, and the mass of the He-core, M_{α}, with respect to stellar models with no mass loss. This is possible when nucleosynthesis calculations are performed on bare He-cores (for example Arnett 1978,1990; THN). However, the net effect of mass loss by stellar wind on M_{α} is still controversial. Originally, Chiosi et al.(1978, 1979) found a lower M_{α} as a consequence of mass loss with respect to conservative models. Later Maeder (1981,1983,1985) did not find any sensitive difference with respect to conservative models (within 10%) (but see Maeder, 1990).

Another important effect on the chemical yields from massive stars is represented by assuming core-overshooting in the stellar models (for extensive reviews on this subject see Chiosi and Maeder, 1986; Chiosi, 1986).

Classically, the extension of a stellar convective core is set at the layer where the acceleration of the fluid elements is zero. However, the zero acceleration point does not coincide with the zero velocity point. Consideration of this effect leads to the so-called "overshooting". The most recent work on the subject is from Maeder and Meynet (1989) (hereafter MM89). Given the uncertainties present in the theory of convection in stellar interiors, the amount of overshooting has been parametrized. During recent years various studies of stellar evolution have caused the overshooting parameter to fluctuate. What is clear is that the main effect of overshooting in massive stars is to enlarge the mass of the He-core with respect to classical stellar models. This leads to a net increase in the production of He and metals.

In spite of the large number of theoretical calculations none of those published until now can explain the observational finding (Peimbert, 1986) that the ratio between He and metal production during galactic lifetime, $\frac{\Delta Y}{\Delta Z}$, is of the order of 3 to 5. All the models published insofar predict a $\frac{\Delta Y}{\Delta Z}$ not larger than 1, unless one makes the "ad hoc" assumption that some massive stars end their life by imploding to black holes instead of exploding like SNe (Schild and Maeder, 1984).

Another solution could be represented by adopting a mass loss rate in massive stars much bigger than those adopted up to now. Maeder (1990) in a very recent paper has recomputed stellar tracks with new opacity tables accounting for non solar ratios at low metallicities of α–elements and Na and Al.The deviations from solar proportions are taken from Lambert (1987). A new rate of mass loss is adopted which depends on metallicity and mass of WR stars, resulting in a larger mass loss rate than previously used. Moderate overshooting is also included. In this case, as a result of the huge mass loss rate, the value of $\frac{\Delta Y}{\Delta Z}$ is predicted to be of the order of 2.

In this paper we will review the nucleosynthesis in massive stars compared with the SN 1987A in LMC (section II).

Then the effect of the evolution and nucleosynthesis in massive stars on the evolution of galaxies will be discussed. In particular, the effect of massive stars on the evolution of

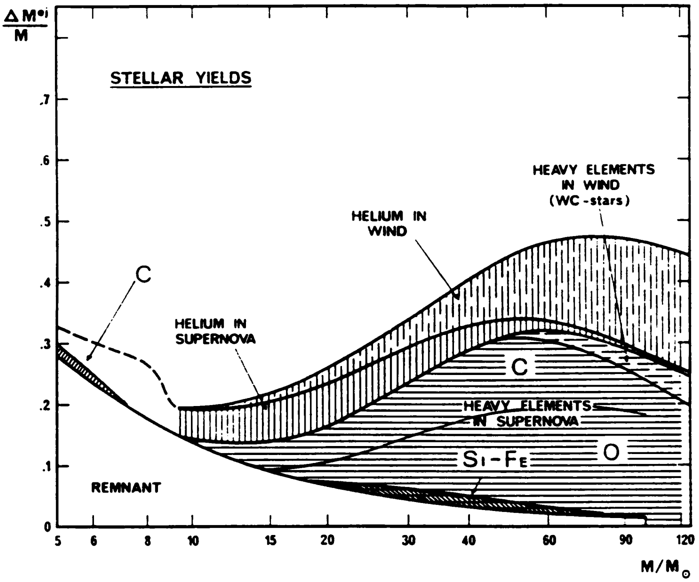


Fig. 1- Mass fraction of He and heavy elements, ejected through stellar winds and supernovae, as a function of the initial stellar mass. The yields from type I SNe are not taken into account. The figure is taken from Chiosi and Maeder (1986).

abundances and abundance ratios in galaxies (section III).

Finally, attention will be devoted to the final fate of massive stars and in particular to the identification of the mass range for progenitors of type II and Ib SNe (section IV). In fact, while there is a general consensus on the fact that massive stars should be the progenitors of type II SNe, although we do not know the upper mass limit for stars becoming such SNe, the progenitors of type Ib SNe are still controversial. Many authors identifie the progenitors of type Ib SNe with WR stars. Alternative models have been proposed involving white dwarfs in binary systems and at the present status of knowledge it is difficult to choose among different scenarios.

II. Massive star nucleosynthesis and SN1987A

The yields of chemical elements, namely the fractions of stellar material in the form of newly created elements, ejected into the ISM through stellar winds and SN explosions, with respect to the material locked up in low mass stars and remnants, depend crucially on stellar evolution and nucleosynthesis. In the following we will focus only on massive stars, which are known to be the major source of heavy elements.

In recent years, several reviews on massive star evolution appeared (see for example Chiosi and Maeder, 1986).

Before discussing the most recent nucleosynthesis results on massive stars we would like to briefly summarize here the most important aspects of the evolution and nucleosynthesis of massive stars:

- $9 \leq M/M_\odot \leq 12$. These stars ignite carbon non-degenerately and those which have cores between 2.2 and 2.5 ignite oxygen in a degenerate Ne-O core. For those with He-cores from 2.5 to 3 $M_\odot$ all six burning stages are ignited non-degenerately and a Fe-core in hydrostatic equilibrium is eventually formed. It is worth noting that the initial mass range $9 - 12 M_\odot$ derives from classical stellar models. If overshooting is taken into account this mass range becomes $6.6 - 10 M_\odot$ (MM89). These stars end their lives as type II SNe and contribute mostly to the enrichment in He and very little in heavy elements (some C and N, see Hillebrandt 1985). In fact, these stars are only enriched in heavy elements in their collapsing cores and since they leave a neutron star as a remnant it is obvious that they eject material of essentially unprocessed composition.

- $12 < M/M_\odot \leq M_{uSNII}$. These stars are responsible for producing the bulk of heavy elements such as O, Ne, Mg, Si, S, Ar, Ca etc. and possibly r-process elements. Some ^{56}Fe , $\simeq 1/3$ of the total Galactic iron, is likely to be produced in these stars as a result of explosive nucleosynthesis occurring in the Si-Ca layers, whereas the bulk of iron should be produced in type I SNe (Matteucci and Greggio, 1986). The amount of iron measured in SN1987A by Danziger et al. (1990), $\simeq 0.08 M_\odot$, confirms that iron production should take place in massive stars. From the theoretical point of view, the amount of iron synthesized in massive stars is quite uncertain, depending on details of the explosion mechanism which is not yet well understood.

M_{uSNII} is the upper mass limit for a star to explode like a type II SN and is practically unknown. One could assume that $M_{uSNII} = M_{lWR}$ where M_{lWR} is the minimum Main Sequence mass necessary for a star to become WR. This mass is also quite uncertain depending on the amount of mass loss and overshooting adopted in stellar models. MM89 suggested $M_{lWR} \simeq 40 M_\odot$. Therefore, if only stars in the mass range $9 - 40 M_\odot$ become type II SNe, which is the fate of WR stars? They will eventually explode, but lacking the hydrogen envelope their light curve and spectra would be different from type II SNe. It has been suggested either that they could be the progenitors of SNe such Cas A (see for example Chevalier and Kirshner, 1978) or that they could be the progenitors of subluminous type I SNe, known as type Ib SNe (see for example Gaskell et al., 1986).

Wolf-Rayet stars contribute to He, N , ^{22}Ne, ^{26}Al and ^{12}C enrichment (Maeder, 1981,1983,1985; Dearborn and Blake, 1984; Prantzos et al. 1985). While their contribution to He, N, ^{26}Al and ^{22}Ne is important (probably they are responsible for the whole galactic ^{22}Ne), their contribution to C is negligible when compared to the SN contribution and to the global C production, either because the bulk of this element is likely to come from intermediate mass stars or because of the paucity of WR stars of type WC in the IMF.

Type II SNe are thought to leave compact remnants which can be neutron stars or black holes. The limiting mass for the formation of black holes is very uncertain as well as if stars leaving black holes do explode or implode. The neutron star mass is also an uncertain quantity, due to the uncertainties in the explosion mechanism, although some constraints are given now by the amount of Fe measured in SN1987A, which allows one to fix the mass cut between neutron star and ejecta in a star with initial mass of $20 M_\odot$.

- $M > 100 M_\odot$. These stars should explode during O burning due to "pair instability". Recent models by MM89 suggest that the range for pair creation SNe should be $100–200 M_\odot$, in agreement with prevoius studies. From the point of view of galactic enrichment, these objects would mostly contribute to oxygen (Ober et al.1983).

- Supermassive objects. Are those which either collapse directly to black holes or suffer total disruption due to explosive H-burning. Masses larger than $7.5\,10^5$ should end up as black holes (Appenzeller and Fricke, 1972), whereas masses in the range $4.1\,10^2 - 7.5\,10^5$ should suffer total disruption during H-burning. The results are very sensitive to the initial stellar metal content and explosion seems possible only for solar metal content. These objects produce mostly He and traces of ^{15}N and ^{7}Li (Woosley et al., 1984).

The most recent nucleosynthesis results on massive stars are those that appeared after SN1987A in LMC. In particular, WPW calculated the detailed isotopic composition of the ejecta of stars with masses of 18 and 20 $M_\odot$, respectively. The model for the $18M_\odot$ star was computed by assuming two different precriptions for the rate of $^{12}C(\alpha,\gamma)^{16}O$ reaction, which is one of the major free parameters in stellar evolution : i)the value suggested by Caughlan et al. (1985) and ii) the very recent one suggested by Caughlan and Fowler (1988) which is a factor of three lower than the previous one. The model with the lower rate predicts an amount of ^{56}Ni of $\simeq 0.07M_\odot$, in very good agreement with what is observed. However, it should be taken into account the fact that some ^{56}Ni can fall back onto the neutron star. Moreover, the model with the small rate is overly rich in neon and deficient in oxygen, so that the authors concluded that an intermediate value of the rate, between i) and ii) should be preferred.

THN calculated the evolution of a He-star of $6M_\odot$, corresponding to the He-core of a $20M_\odot$ star and the composition of its ejecta after explosion. They adopted the rate of Caughlan et al.(1985) for the $^{12}C(\alpha,\gamma)^{16}O$ reaction. The amount of ^{56}Ni in this case was fixed by the observed Fe mass in SN1987A.

Detailed nucleosynthesis for He-core masses between 2.7 and $32M_\odot$, corresponding to initial masses between 10 and $85M_\odot$, including, of course, a $20M_\odot$ star, was very recently presented by Arnett (1990). Also in this case a mass cut was imposed for the $20M_\odot$ model by the observed iron in SN1987A.

All these calculations differ in the various assumptions on the input physics, and details can be found in the quoted papers. We show in Table I the observed (at day 410 after explosion) amounts of several species in SN1987A from Danziger et al. (1990), compared with different nucleosynthetic models for a $20M_\odot$ star. It should be noted that the observed values for Fe and Ni seem to be reasonably secure, whereas the estimated mass of oxygen is still very uncertain, going from 0.2 up to $3M_\odot$.

In spite of the uncertainties both in theory and observations, an inspection of Table I shows that the agreement between predictions (column 3,4 and 5) and data is reasonably good, except for the amount of Ni predicted by THN, which is larger by more than a factor of ten with respect to the observed value. Therefore observations (assuming that all the

Table I:
Observed and predicted abundances for SN 1987A

Species	Observed$^{1)}$	WPW(88)$^{2)}$	THN(90)$^{3)}$	Arnett(90)
C	0.072	0.18	0.114	0.288
O	0.2÷3.0	1.6	1.48	0.774
Si	0.102	0.11	0.085	—
Ar	>0.0008	0.011	0.00377	—
Ca	<0.0105	0.0096	0.00326	—
Fe	0.0825	0.14	0.076	0.07
Ni	0.0022	0.0044	0.0197	—

1) Danziger *et al.* (1990)
2) Woosley *et al.* (1988)
3) Thielemann *et al.* (1990)

Ni mass is observed), can put serious constraints on stellar models. THN discussed the possibility of removing this discrepancy either by i) changing the mass cut or ii) alterating the stellar model. Comparison of the theoretical predictions shows differences inside a factor of 2-3, except for the predicted Ni which differ by a factor of 5 between THN and WPW.

III. Massive stars and galactic evolution

Models of chemical evolution for the solar neigbourhood and the whole disk including detailed nucleosynthesis from type Ia, Ib and II SNe, have been recently computed by Matteucci and François (1989) and Matteucci (1990). These models assumed nucleosynthesis prescriptions from WW in the domain of massive stars, whereas for low and intermediate mass stars (between 0.8 and $8M_{\odot}$) the results of Renzini and Voli (1981) were adopted. For the nucleosynthesis in type Ia SNe (C-O white dwarfs exploding by C-deflagration in binary systems), prescriptions from Nomoto et al. (1984, their model W7) were taken into account. These SNe produce $\simeq 0.6M_{\odot}$ of iron plus traces of C-Si elements. The progenitor model assumed for type Ib SNe was a C-O white dwarf merging after gravitational wave radiation with an He-non-degenerate star and exploding by He-off center detonation. (Iben et al., 1987; Tornambè and Matteucci, 1987) In this case, a maximum amount of iron of $\simeq 0.3M_{\odot}$ is produced.

The nucleosynthesis prescriptions of WW refer only to the presupernova configuration and some assumptions on the explosive nucleosynthesis had to be made. In particular, it was assumed (Woosley, private communication) that the ejected iron is produced by explosive nucleosynthesis on Si-Ca elements and that stars with $M < 12M_{\odot}$ do not produce iron at all, whereas stars with masses between 12 and $20M_{\odot}$ produce an increasing amount of iron with a maximum of $0.1M_{\odot}$ for a $20M_{\odot}$ star, which is a very good approximation when compared to the amount of iron measured in SN1987A. Finally, for stars with masses larger than $20M_{\odot}$ it was assumed that they produce a maximum of $0.4M_{\odot}$ of iron (which is probably an overestimate).

It was also assumed that part of the Si-Ca elements falls back into the collapsing core before explosion starts. In particular, the parameter which describes this fraction of material has been constrained to reproduce the more recent nucleosynthesis results of WPW for a $20M_{\odot}$ star (see Table I).

For elements such as He and N, which are lost mainly through stellar winds in massive stars, prescriptions from Maeder (1981;1983) were taken into account.

In this paper, we show new results obtained with recent yields calculated by Arnett (1990), and we compare them with the previous results and with the observations. In Fig. 2 the predicted $|O/Fe|$ vs.$|Fe/H|$ for the solar neighbourhood region is shown. The two curves refer to the predictions obtained with the two different yields from massive stars, as described above, and they are practically identical. The same is true for α-elements (Ne, and Mg) In Fig. 3 is reported, as an example, the predictions for $|Mg/Fe|$ vs. $|Fe/H|$. No comparison is made for Si and S because in Arnett's calculation Si-Ca elements are not distinguishable.

In Fig. 4 are shown the predicted $|C/Fe|$ vs. $|Fe/H|$ obtained with the two different prescriptions. In this case, the predictions differ in a non negligible way. The reason for this can be attributed either to different treatments of convection or to different rates dopted for the major reaction rates.

From the observational point of view, while the behaviour of O and α-elements seems to be fairly well established (Wheeler et al., 1989), many uncertainties are still present in the data relative to C and N. The carbon/iron ratio, in particular, appears to be roughly solar for stars with $|Fe/H| > -2.0$. However, some of the data indicate that for $|Fe/H| \leq -2.5$, C could be overabundant with respect to iron.

In any case, a comparison between theory and observations is difficult in the case of C, due to the uncertainties present in the nucleosynthesis results for low and intermediate

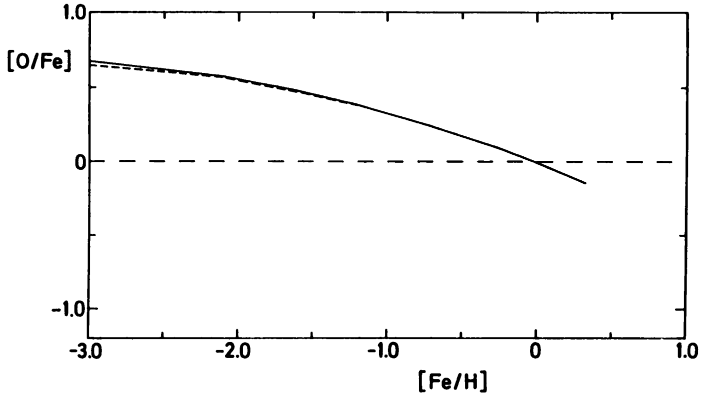


Fig. 2- Predicted $|O/Fe|$ vs. $|Fe/H|$ relations. The continuous line refers to a model adopting Arnett's (1990) yields from massive stars whereas the dotted line refers to a model adopting WW's results.

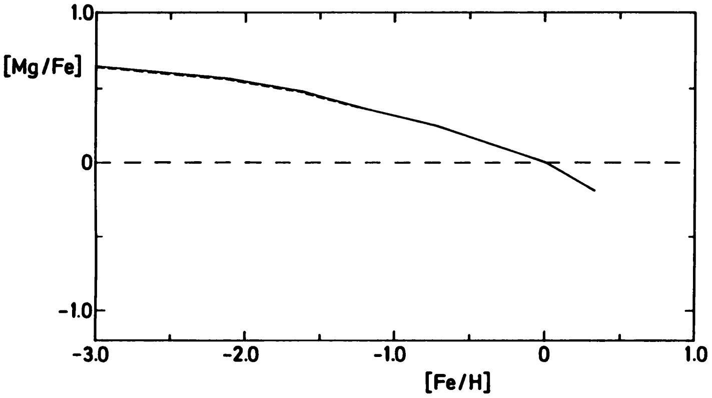


Fig. 3- Predicted $|Mg/Fe|$ vs. $|Fe/H|$ relations. Continuous and dotted lines refer to the same cases as in Fig. 2.

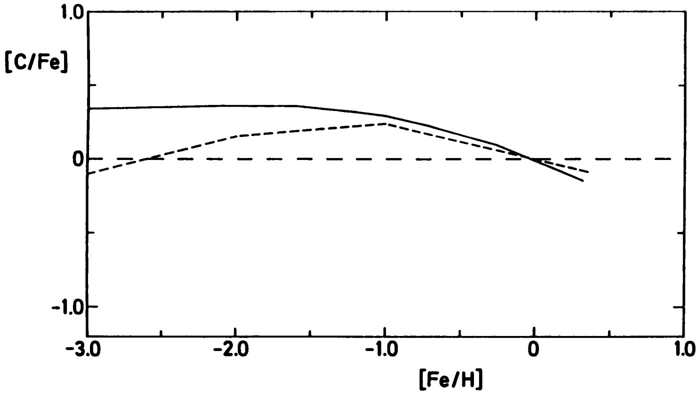


Fig. 4- The same as in Figs. 2 and 3 for $|C/Fe|$ vs. $|Fe/H|$ relations.

mass stars.

From the behaviour of O and α-elements with respect to iron one can easily understand the influence of massive stars on galactic evolution. In fact, it is clear that at low metallicities ($|Fe/H| < -1.0$) massive stars dominate the chemical evolution of the Galaxy, and that the almost constant or slightly declining observed $|O/Fe|$ and $|\alpha/Fe|$ ratios with metallicity reflect the nucleosynthesis in massive stars. The abrupt change in the slope of these relations for $|Fe/H| > -1.0$ is the consequence of the appearence of type I SNe restoring the bulk of iron.

Therefore, the measured $|el/Fe|$ ratios in metal poor stars can impose constraints on nucleosynthesis in massive stars. For example, Matteucci and Greggio (1986) concluded that, although type I SNe should produce the bulk of iron in the Galaxy, type II SNe should also contribute to iron ($\simeq 1/3$ of the total), otherwise the predicted $|O, \alpha/Fe|$ ratios should be continuously declining with the same slope over the whole metallicity range. The measured amount of Fe in SN1987A has confirmed this suggestion.On the other hand, if only type II SNe would produce iron, the $|O, \alpha/Fe|$ ratios would be greater than solar over the whole range of metallicity.

Another and better example of the predominance of massive stars on galactic evolution refers to the Galactic bulge and elliptical galaxies. In a recent paper, Matteucci and Brocato (1990) predicted the $|O, \alpha/Fe|$ vs. $|Fe/H|$ relation for the bulge of our Galaxy, (shown in Fig. 5) and the same conclusions apply for elliptical galaxies. In particular, due to the faster evolution of these systems relative to the other Galactic regions the predicted O and α-element ratios with respect to iron are expected to be greater than solar in the majority of bulge stars, and of the same order as those observed in halo stars, which,in fact, have the same age as the bulge stars. Very recently, Barbuy and Grenon (1990) have measured the O/Fe ratio in some bulge stars and the agreement with the predictions seems quite good. In fact, they they have found an average $|O/Fe| = +0.2$ in stars with an average $|Fe/H| = +0.5$. On the other hand, in systems like the Magellanic Clouds or the external regions of the galactic disk, the predominance of massive stars in the chemical enrichment is restricted to a narrower metallicity range, due to the slower evolution of these systems, as shown in Fig. 5. As a consequence, one should expect to find, in the Clouds, oxygen to be underabundant with respect to iron as compared to the solar neighbourhood of the Galaxy. Observational evidence for this has been found by Russel et al. (1988).

Finally, in Table II are shown the predicted solar abundances obtained by using the two different prescriptions for nucleosynthesis in massive stars and compared with Cameron (1982). As one can see, Arnett's prescriptions give an higher abundance for C (by a factor of 1.25) with respect to the abundance obtained with the WW results, and in better agreement with the observed one. On the other hand, the O abundance is lower by a factor of 1.6 relative to the other theoretical result and to the observed value.

Ne and Mg abundances are higher than the corresponding ones in the case of WW's nucleosynthesis by a factor of 2 and 1.7, respectively, and in better agreement with Cameron (1982). The Si-Ca elements(taken as a whole) in Arnett's(1990) case are slightly lower than in WW's case and again in better agreement with the observed values.

The abundance of iron is practically the same in the two models and in good agreement with the observed one. This is due to the fact that massive stars have a little influence on iron abundance which mostly depends on the assumptions made on nucleosynthesis in type I SNe, and those are the same in both models.

IV. Supernova rates and Wolf–Rayet as progenitors of type Ib SNe

In this section we will discuss the effect on galactic evolution of assuming that WR stars are the progenitors of type Ib SNe.

Type Ib SNe were discovered already 20 years ago by Bertola (1964): they are subluminous with respect to type Ia SNe. In particular, the luminosity of the maximum is

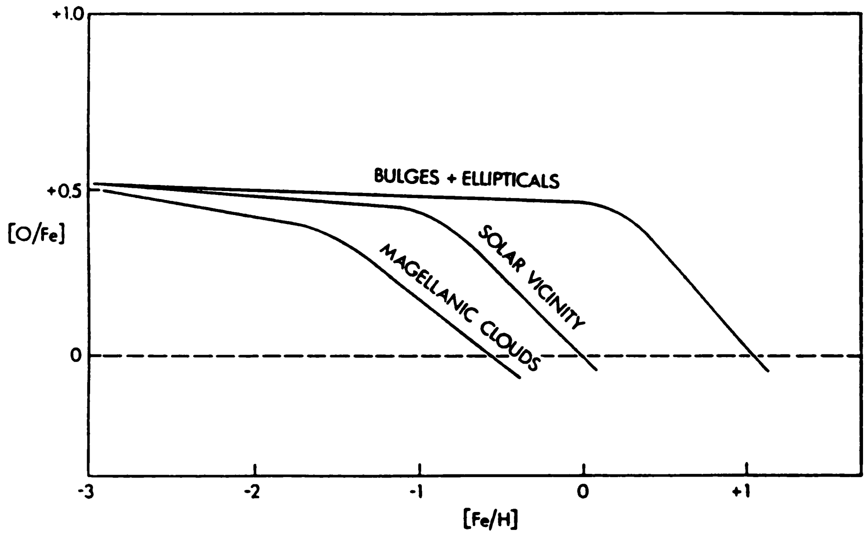


Fig. 5- A rough sketch of the predicted $|O/Fe|$ vs. $|Fe/H|$ relation in different systems, showing their different evolutionary histories. Figure taken from Matteucci and Brocato (1990).

Table II: Predicted and Observed Solar Abundances

	WW(86)	Arnett(90)	Cameron(82)
X_{H}	0.742	0.74	0.772
$X_{12_{\mathrm{C}}}$	2.75(−3)	3.45(−3)	3.87(−3)
X_{O}	8.8(−3)	5.25(−3)	8.55(−3)
X_{N}	9.2(−4)	7.2(−4)	9.34(−4)
$X_{13_{\mathrm{C}}}$	3.3(−5)	2.82(−5)	4.64(−5)
X_{Ne}	7.0(−4)	1.4(−3)	1.34(−3)
X_{Mg}	3.5(−4)	6.00(−4)	5.81(−4)
X_{Si}	8.13(−4)	1.2(−3)	7.49(−4)
X_{S}	4.57(−4)		4.41(−4)
X_{Ca}	1.0(−4)		7.04(−5)
X_{Fe}	1.44(−3)	1.2(−3)	1.33(−3)

1.5–2.0 magnitudes fainter than that of type Ia SNe. As a consequence, their light curves can be explained by an amount of Fe of $0.1 - 0.2 M_\odot$, as opposed to the $\simeq 0.6 M_\odot$ of Fe necessary to power the light curve of type Ia SNe.

Type Ibs seem to occur in spiral arms or close to HII regions (Porter and Filippenko, 1987), although this finding has been questioned by Panagia (1990). Moreover, in contrast with type Ia, type Ib seem to be strong radio emitters. This has been interpreted in favour of WR stars as progenitors (but see again Panagia, 1990). Frequency estimates suggest that a fraction of 30 to 60% of all type I SNe are of type Ib (Panagia, 1987; van den Bergh, 1990). Alternative models to WR have been proposed and they involve either white dwafs in binary systems (Branch and Nomoto, 1986; Iben et al., 1986; Tornambè and Matteucci, 1987), or He-stars of $3 - 4 M_\odot$ (with Main Sequence progenitors in the mass range $12 - 16 M_\odot$) in binary systems (Shigeyama et al., 1990).

WR models have problems in reproducing the light curves of typical type I b SNe, in producing the right amount of ^{56}Ni and the observed frequency of these SNe, given the paucity of WR stars in the IMF. In fact, if only stars with masses greater than $40 M_\odot$ become WR stars (MM89) then the expected type Ib SN frequency would be too low, even adopting a Salpeter (1955) IMF, which favours massive stars with respect to other IMFs more suitable for the solar neighbourhood (Scalo, 1986). One possible solution could be to assume that all stars with mass greater than $\simeq 16 M_\odot$ become WR, but this is probably an unrealistic assumption.

On the other hand, by assuming that type Ib SNe originate from white dwarfs in binary systems one does not have any difficulty in reproducing the observed frequencies of all SN types. In a recent review, van den Bergh (1990) concludes that the best current estimate for the total Galactic SN rate is $\simeq 2$ per century. Of these supernovae $\simeq 18\%$ are expected to be of type Ia, $\simeq 17\%$ of type Ib and $\simeq 65\%$ of type II.

Matteucci and François (1989), by adopting Scalo's IMF, predicted the following rates for our Galaxy: $0.4 SNe 100 yr^{-1}$ for type Ia, $0.4 SNe 100 yr^{-1}$ for type Ib and $1.1 SNe 100 yr^{-1}$ for type II SNe, in very good agreement with van den Bergh's estimates. These rates were obtained by assuming that type II SNe come from stars in the mass range $9 - 100 M_\odot$, whereas type I SNe come from C-O white dwarfs in binary system, therefore from stars with initial masses $\leq 8 M_\odot$.

If WR stars, instead of C-O white dwarfs, are assumed as progenitors of type Ibs, the same model predicts: $\simeq 0.4 SNe 100 yr^{-1}$ for type Ia, $\simeq 0.06 SNe 100 yr^{-1}$ for type Ib and $\simeq 1.045 SNe 100 yr^{-1}$ for type II. Therefore, while the total type II rate in not affected by this assumption, the type Ib rate results too low by a factor of $\simeq 6.5$ with respect to the case with white dwarfs as progenitors and to the observed one. Only if one assumes that WR stars originate from all stars greater than $\simeq 15 - 16 M_\odot$, the type Ib rate raises up to $0.35 SNe 100 yr^{-1}$, while the type II rate is still acceptable. Therefore, from the point of view of the SN frequencies the white dwarf model for progenitors of type Ib should be favoured.

From the point of view of the predicted solar abundances, the model with the WR stars as progenitors of type Ibs predict a slightly smaller iron abundance with respect to the other case. In particular, a model where the Arnett (1990) yields are adopted, predicts a solar iron abundance of $8.4 10^{-4}$, which is still acceptable, while the other abundances are left unchanged. This lower solar iron abundance leads also to slightly lower overabundances of O and α-elements with respect to iron at low metallicities, but always inside the observational uncertainties. In conclusion, the differences between the abundance results obtained for the solar neighbourhood under the two different assumptions on the type Ib progenitors, do not allow us to distinguish between the two scenarios.

References

Appenzeller, I., Fricke, K.J.: 1972, *Astron. Astrophys.* **18**, 10

Arnett, W.D.: 1978, *Astrophys. J.* **219**, 1008

Arnett, W.D.: 1990, in *Chemical and dynamical evolution of galaxies*, ed. F. Ferrini et al., (Giardini:Pisa), in press

Barbuy, B., Grenon, M.: 1990, in *Bulges of Galaxies*, ESO/CTIO workshop, in press

Bertola, F.: 1964, *Ann. Astrophys.* **27**, 319

Branch, D., Nomoto, K.: 1986, *Astron. Astrophys.* **164**, L13

Cameron, A.G.W.: 1982, in *Essays in nuclear astrophysics*, ed. C. Barnes et al., (Cambridge University Press), p.377

Caughlan, G.R., Fowler, W.A., Harris, M.J., Zimmerman, B.A.: 1985, *Atomic Data and Nuclear Data Tables* **32**, 197

Caughlan, G.R., Fowler, W.A.: 1988, *Atomic Data and Nuclear Data Tables* **40**, 283

Chevalier, R.A., Kirshner, R.P.: 1978, *Astrophys. J.* **219**, 931

Chiosi, C.: 1986, in *Nucleosynthesis and chemical evolution* ed. B. Hauck et al. (Geneva Observatory Publ.), p.199

Chiosi, C., Maeder, A.: 1986, *Ann. Rev. Astron. Astrophys.* **24**, 329

Chiosi, C., Nasi, E., Bertelli, G.: 1979, *Astron. Astrophys.* **74**, 62

Chiosi, C., Nasi, E., Sreenivasan, S.R.: 1978, *Astron. Astrophys.* **63**, 103

Danziger, I.J., Lucy, L.B., Bouchet, P., Gouiffes, C.: 1990, in *Supernovae*, ed. S.E. Woosley (Springer Verlag: New York), in press

Dearborn, D.S., Blake, J.B.: 1984, *Astrophys. J.* **277**, 783

Gaskell, C.M., Cappellaro, E., Dinerstein, H.L., Garnett, D.R., Harkness, R.P., Wheeler, J.C.: 1986, *Astrophys. J. (Lett.)* **306**, L77

Hashimoto, M., Nomoto, K., Shigeyama, T.: 1989, *Astron. Astrophys.* **210**, L5

Hillebrandt, W.: 1985, in *Production and distribution of CNO elements*, ed. I.J. Danziger et al. (E.S.O. Publ.) p.325

Hillebrandt, W.: 1987, in *High energy phenomena around collapsed stars*, ed. F. Pacini (Reidel: Dordrecht) p.73

Iben, I. jr., Nomoto, K., Tornambè, A., Tutukov, A.: 1987, *Astrophys. J.* **317**, 717

Lambert, D.L.: 1987, *J. Astrophys. Astr.* **8**, 103

Maeder, A.: 1981, *Astron. Astrophys.* **102**, 299

Maeder, A.: 1983, *Astron. Astrophys.* **120**, 113

Maeder, A.: 1985, in *Nucleosynthesis and its implications on nuclear and particle physics*, ed. J. Audouze and N. Mathieu (Reidel: Dordrecht), p.207

Maeder, A.: 1990, preprint

Maeder, A., Meynet, G.: 1989, *Astron. Astrophys.* **210**, 155 (MM89)

Matteucci, F.: 1990, in *Frontiers of stellar evolution*, ed. D.L. Lambert, P.A.S.P., in press

Matteucci, F., Brocato, E.: 1990, *Astrophys. J.*, in press

Matteucci, F., François, P.: 1989, *M.N.R.A.S.* **239**, 885

Matteucci, F., Greggio, L.: 1986, *Astron. Astrophys.* **154**, 279

Nomoto, K., Thielemann, F.K., Yokoi, Y.: 1984, *Astrophys. J.* **286**, 644

Ober, W., El Eid, M., Fricke, K.J.: 1983, *Astron. Astrophys.* **119**, 61

Panagia, N.: 1987, in *High energy phenomena around collapsed stars* ed. F. Pacini (Reidel: Dordrecht) p.33

Peimbert, M.: 1986, *P.A.S.P.* **98**, 1057

Porter, A., Filippenko, A.: 1987, *Astron. J.* **93**, 1372

Prantzos, N., Arcoragi, J.P., Arnould, M.: 1985, in *Nucleosynthesis and its implications on nuclear and particle physics*, ed. J.Audouze and N. Mathieu (Reidel: Dordrecht), p.293

Renzini, A., Voli, M.: 1981, *Astron. Astrophys.* **94**, 175

Russel, S.C., Bessel, M.S., Dopita, M.A.: 1988, in *The impact of high S/N spectroscopy on stellar physics*, ed. G. Cayrel de Strobel and M. Spite (Reidel: Dordrecht), p.545

Salpeter, E.E.: 1955, *Astrophys. J.* **121**, 161

Scalo, J.H.: 1986, *Fund. Cosmic Phys.* **II**, p.1

Schild, H., Maeder, A.: 1984, *Astron. Astrophys.* **143**, L7
Shigeyama, T., Nomoto, K., Tsujimoto, T.: 1990, *Astrophys. J. (Lett.)* submitted
Thielemann, F.K., Hashimoto, M., Nomoto, K.: 1990, *Astrophys. J.* **349**, 222 (THN)
Tornambè, A., Matteucci, F.: 1987, *Astrophys. J. (Lett.)* **318**, L25
van den Bergh, S.: 1990, in *Supernovae*, ed. S.E. Woosley (Springer Verlag: New York) in press
Wheeler, J.C., Sneden, C., Truran, J.W.: 1989, *Ann. Rev. Astron. Astrophys.* **27**, 279
Woosley, S.E.: 1986, in *Nucleosynthesis and chemical evolution*, ed. B. Hauck et al. (Geneva Observatory Publ.), p.1
Woosley, S.E., Axelrod, T.S., Weaver, T.A.: 1984, in *Stellar nucleosynthesis*, ed. C. Chiosi and A. Renzini (Reidel: Dordrecht), p.263
Woosley, S.E., Pinto, P.A., Weaver, T.A.: 1988, *Proc. ASA* 7(4), 355 (WPW)
Woosley, S.E., Weaver, T.A.: 1986, in *I.A.U. Coll. n. 89* ed. D. Mihalas and K.A. Winkler, p.91 (WW)

DISCUSSION

Vanbeveren: All stars with initial mass larger than $10M_\odot$ which are member of a close binary end their life as hydrogen deficient stars (as a consequence of Rocke lobe overflow). I remind you that this has nothing to do with the WR phenomenon. If then one assumes $8M_\odot$ as minimum mass for single stars to explode (most of them as Type II), $10M_\odot$ as minimum mass for close binaries to explode, taking a 30% close binary frequency, and assuming some IMF, one ends up with a $\sim$ 20% massive ($M > 10M_\odot$) star frequency which will explode hardly showing any hydrogen at all. So, the 17% you give nicely coincides with the $\sim$ 20% I give here. I therefore conclude that as far as frequencies are concerned Type Ib agrees with the number of massive close binaries.
Matteucci: Yes, I agree.

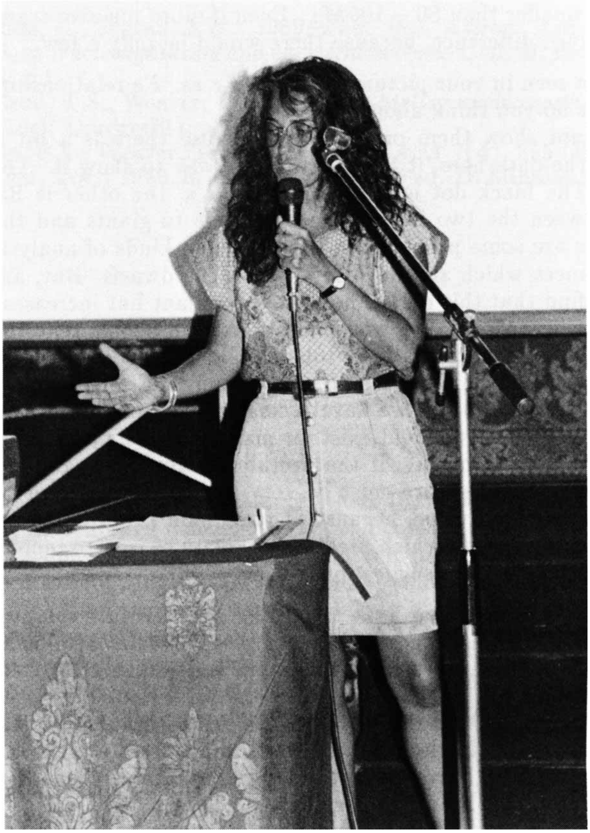
Maeder: Your recent results on the different behaviours of the O/Fe ratios in elliptical galaxies and other galaxies, the solar vicinity and the Magellanic cloud, are a magnificent piece of work. Do you already have comparisons of your model available with abundances determined in highly redshifted galaxies observed in the Lyman forest of QSO? Because, in these highly redshifted galaxies you should also have some massive stars which contribute to the nucleosynthesis.
Matteucci: Unfortunately, I do not have, but that is a very good point in fact, to compare evolution with iron red shift.

Nomoto: (1) Helium detonation in some accreting white dwarfs is a natural outcome of evolution theory. Its explosion would be observed not as SNIb but SNI-F, *i.e.*, fast decline-type of SNI (like S And) which would easily be missed from observations. So chemical evolution models should not neglect SNI-F; (2) In your model, how is the abundance gradient in the galactic disk formed?
Matteucci: (2) The abundance gradient in the galactic disk, form, in my model, as a consequence of assuming different time scales for disk formation at different galactocentric distances. In particular, the time scale for disk formation increases with galactocentric distance. For more details, see Matteucci and Francois (1989).

Heydari-Malayeri: I saw in one of your viewgraphs that you have considered extremely high mass stars. There is no reliable observational evidence for the existence of stars more massive than $100 M_\odot$. There is a poster by us outside on display. I think that this is an important point to keep in mind.
Matteucci: I only mentioned very massive stars, but in fact I included in my models only stars with masses smaller than $80 - 100 M_\odot$. Even if more massive stars would exist, they would not make much difference, because there would be only a few.

Vilchez: I have not seen in your picture of the O/Fe *vs.* Fe relationship, the data of Abia and Rabolo. What do you think about that?
Matteucci: I did not show them on purpose, because there is a bit of a discussion on them, and I have the data here, it is important anyway to show it. This is the O/Fe *vs.* Fe relationship. The black dot is Abia and Rabolo's, the other is Barbieu and others. The difference between the two is that the one refers to giants and the other to dwarfs, and probably there are some problems in both of these kinds of analysis. The giants give always overabundances which are much lower than the dwarfs. But, another difference is that they seem to find that this part is not really constant but increases. Now I have been to many meetings where also Rafael was, and others, and people tend to say: "I am not an observer", so, I have to trust them, but probably the truth is in the middle, because these stars here, the dwarfs, may have the problems of non-LTE and I do not know about the giants. So, at the moment, untill we have a confirmation of this, I would expect that, if this trend exists for oxygen, it should exist for magnesium, *e.g.*, whereas it does not. But, if it was true, what does it mean? If the overabundance of oxygen is so high, it means that the iron in very massive stars must be very little or none. And so, the yield that I use would not give this high value, because at maximum I find 0.6, and I use the yield of Woosley and Waever or Arnett which predicts the mass of iron to increase with the initial mass of the star. Let us use the suggestion of Ken.

Filippenko: I want to clarify one issue regarding the absolute quantity of iron (in the Galaxy) produced by different types of supernovae. If SNeIa, SNeIb, and SNeII produce $0.6 M_\odot, 0.15 M_\odot$, and $0.10 M_\odot$ of Fe, respectively, and the relative frequencies of SNeIa, SNeIb, and SNeII are 18%, 17%, and 65%, then the total production rate of iron in SNeIb and SNeII is *comparable* to that of SNeIa. Taking into account the fact that SNeIb and SNeII were more numerous in the past (where SNeIa were not), the total amount of Fe produced by SNeIb and SNeII *exceeds* that produced by SNeIa. Thus, the *absolute* quantity of Fe is *not* dominated by SNeIa in our galaxy.
Matteucci: Yes, you are right. The different contributions to total galactic iron from the various SN types from my model are: 23% Type II, 25% Type Ib and 50% Type Ia. So, the total contribution of Type II and Type Ib SNe is comparable to the contribution of Type Ia. When I said that Type Ia SNe dominate the galactic production of iron, I meant in comparison with the contribution of Type II and Type Ib SNe, separately.



Francesca Matteucci