55

OBSERV C 129-1994
SW 9426

PUBLICATIONS DE L'OBSERVATOIRE DE GENÈVE

CERN LIBRARIES, GENEVA

P00024095

Physical processes in stellar evolution

André Maeder

Review paper to be published in Physical processes in astrophysics, Springer, 1994 (in press)

Série C :

PRÉ - PUBLICATIONS

Fascicule 129 (1994)

Chemin des Maillettes 51
CH-1290 Sauverny / Suisse

Fax (41 22) 755 39 83
Tél. (41 22) 755 26 11
Telex (45) 419 209 obsg ch

Physical Processes in Stellar Evolution

André Maeder

Geneva Observatory, CH 1290 Sauverny, Switzerland

Abstract: We firstly examine the possible roles of mass loss and mixing as a function of stellar masses. Then we review the present observational status about additional mixing processes in massive stars. Various evidences from main-sequence OB stars, from blue supergiants, from SN 1987A and from Wolf-Rayet stars are given in favour of a significant mixing in radiative zones of rapidly rotating massive stars. We also particularly examine the role of mass loss on the ratio $\Delta Y/\Delta Z$ of the relative helium-to-metal enrichments. We show that mass loss is far from sufficient to explain the high observed $\Delta Y/\Delta Z$ ratios. We suggest that swallowing of heavy elements in black holes occurs. In order to account for the observed $\Delta Y/\Delta Z$ ratios in low Z HII regions, it is necessary that black holes form above initial masses of about $20 M_{\odot}$.

1 Introduction

Up to the 18th century, a scholar could be an expert in all sciences. In the middle of the 20th century, it was still possible for some great astrophysicist to master all scientific fields. The famous book “Astrophysique Générale”, written in 1959 by J.C. Pecker and E. Schatzman, was such an example where all parts of astronomy were masterly enlightened with a deep physical insight. Today the evolution of sciences is such that it is even no longer possible for a single astrophysicist to master all problems of stellar structure and evolution from star formation to compact objects. Thus, what will be the future? The astronomers will likely have to keep a proper balance between their own highly specialized research and a sound overview of the whole astrophysical field. The balance, however, will be more and more delicate to adjust and this can be done only on the basis of a deep formation in the study of astrophysical processes.

After this introduction I feel barely allowed to concentrate on a limited number of important problems in stellar evolution. I shall consider particularly mass loss and mixing, which have such large consequences for stellar evolution and nucleosynthesis.

2 Mass loss and mixing throughout the HRD

2.1. Mass loss in massive stars

Mass loss by stellar winds is a dominant feature of massive star evolution. It is so important that stars with initial mass above $30 M_{\odot}$ nearly completely evaporate during their evolution. All model outputs are concerned (cf. Chiosi and Maeder 1986; Maeder and Conti 1994): HR diagram, chemical abundances, number statistics, chemical yields, supernova progenitors etc. Wind models have been developed by several groups; however the observed mass loss rates and the wind momentum in O-stars are generally larger than predicted as shown by Lamers and Leitherer (1993). Thus, it is better to base the models on the observed mass loss rates (cf. Nieuwenhuijzen and de Jager 1990). The average rate is:

$$\dot{M} = -10^{-7.93} \frac{L^{1.64} M^{0.16}}{T_{\text{eff}}^{1.61}} M_{\odot} \text{ yr}^{-1}$$

where L and M are in solar units. The mass fraction lost during the evolutionary lifetime t_{ev} is

$$\frac{\Delta M}{M} = \frac{\langle \dot{M} \rangle}{M} \cdot t_{\text{ev}}$$

With t_{ev} and the mass-luminosity relation given by (between 20 and $85 M_{\odot}$)

$$t_{\text{ev}} = 10^{7.87} M^{-0.72} \text{ yr}$$

$$L = 10^{1.83} M^{2.17} L_{\odot}$$

one obtains

$$\frac{\Delta M}{M} \sim M^2$$

This shows that the initially most massive stars not only loose more mass, but also a larger fraction of their mass during the evolution, and thus they have smaller final masses at the time of supernova explosions (cf. Fig. 1).

The above results concern solar metallicity. For other metallicities we have to know in particular how metallicity influences the mass loss rates. A dependence of $\dot{M}$ on Z^{α} with $\alpha = 0.5 - 0.7$ has been suggested for O-star models (Kudritzki et al. 1987; Leitherer and Langer 1991). Thus, at high Z , massive stars enter the Wolf-Rayet (WR) stage early, which corresponds to the visibility of the bare core. In the WR stage the stars follow a $\dot{M}$ vs M relation, with an exponent of about 2.5 (cf. Langer 1989). The WR stage drastically contributes to the decrease of the stellar masses. Figure 1 summarizes the effects of mass loss for massive stars as a function of Z ; it is based on the results by Schaller et al. (1992) and Meynet et al. (1994). It shows the nearly full evaporation of massive stars at solar or high Z and also the great differences in the final evolution according to metallicities.

Fig. 1. The final stellar masses as a function of initial stellar masses for various metallicities Z . For massive stars this is the mass in the pre-supernova stage (cf. Maeder 1992). The case of mass loss rates twice as large at $Z = 0.02$ is also illustrated.

2.2. Mass loss in low mass stars

IR photometry completed at longer wavelengths by VLA and IRAS photometry observations has allowed to find rather enormous mass loss rates in some M-dwarfs (cf. Mullan et al. 1992). The key point is that a large mass loss rate produces an optically thick wind at long wavelengths due to free-free absorption. The location of the photospheric radius in the thick winds varies with frequency, so that the flux should go like $\nu^{0.7}$. Mullan et al. effectively observe a long tail with the corresponding slope in the spectra of some M-dwarfs. The intensity of this tail at long wavelengths allows the authors to determine a mass loss rate of about $10^{-10} M_{\odot} \text{ yr}^{-1}$ in a few M-dwarfs, in particular in YZ CMi.

Studies of the temporal evolution of the H_{γ} line in the M-dwarf AD Leo by Houdebine et al. (1990) has shown very fast ejection speeds of the plasma (up to 5800 km/s) and gives values of the mass loss rates of the same order as above (see also Fong, this meeting).

Mass loss rates of $10^{-10} M_{\odot}/\text{yr}$ are four orders of magnitude larger than in the Sun. This is a major effect in these stars which have lifetimes of more than 10^{10} years and which could thus lose a substantial part of their masses. Thus, M-dwarfs could be very important injectors into the interstellar material. It is however very critical in this context to establish during which fraction of their lifetime the M-dwarfs reach such important mass loss rates.

2.3. Internal mixing in stellar evolution

Most physical mechanisms of mixing are dissipative and have thus a diffusion coefficient D somehow depending on the viscosity coefficient ν . This is the case for turbulent diffusion (Schatzman and Maeder 1981), for rotational mixing (Zahn 1983, 1992) and also for semiconvective mixing. However, this is not the case for the transport by the action of internal waves studied by Schatzman (1993). In general the characteristic time of mixing is (Schatzman 1977)

$$t_{\text{mix}} = \frac{4}{\pi^2} \left(\int_0^R \frac{dr}{\sqrt{D}} \right)^2$$

i.e. about

$$t_{\text{mix}} \simeq 0.4 \frac{R^2}{\bar{D}}$$

where $\bar{D}$ is an appropriate average. In massive stars, the main viscosity source is radiative viscosity.

$$\nu = \frac{4}{15} \frac{a T^4}{c \kappa \rho^2}$$

Taking $T \simeq \frac{\mu m_H}{k} \frac{GM}{R}$, we see that t_{mix} behaves like

$$t_{\text{mix}} \simeq 0.1 \frac{c}{a} \left(\frac{k}{\mu m_H G} \right)^4 \frac{\kappa}{R_*^2 M^2}$$

where $R_*^2 = D/\nu$ is a factor which may be of the order of a few 10^2 (cf. Maeder 1987b). In Zahn's theory for example D/ν varies from center to surface, but these variations are an order of magnitude smaller than those of ν . The above expression shows a rapid decrease of t_{mix} with stellar masses, indeed much faster than the evolutionary lifetime t_{ev} given in 2.1 and which goes like $M^{-0.72}$. These rough approximations suggest that massive stars are indeed very close to a partial mixing stage, or some may even evolve close to homogeneity (cf. Maeder 1987b). The observations of OB stars support this point of view.

3. Observational status of the problem of mixing in massive stars

As no theory may give firm predictions on mixing in massive stars, it seems essential in this context to examine carefully the present status of observations concerning the occurrence of non-convective mixing processes in massive stars.

3.1. Main sequence

The surface abundances in He and CNO elements offer a powerful test of stellar evolution. Evidences of CN processing are provided by He and N enhancements together with C depletion, while O depletion only occurs for advanced stages of processing. The abundances may cover a range from solar values ($C/N = 4$, $O/N = 10$) to CNO equilibrium values in the extreme case which is reached in WN stars ($C/N = 0.2$, $O/N = 0.1$; Maeder 1987a). Models with mass loss but no extra-mixing predict He and N-enrichments in MS stars only for initial masses larger than about $50 M_{\odot}$ depending on the mass loss rates. Models with rotational mixing may lead to an early appearance of the products of the CNO cycle (cf. Maeder 1987b; Langer 1993). The observations of 25 OB stars by Herrero et al (1992) show that most MS stars have normal He and N abundances. The same is generally true for MS B-type stars. For example, even the most massive object Melnick 42 (O3f) appears to show normal abundance ratios (Pauldrach et al. 1994). However, there are also many exceptions for O and B stars. For example, the O4f star Zeta Pup presents evidences of an atmosphere with CNO burned material (Pauldrach et al. 1994). Fast rotators are also an exception and they generally present He and N enhancements (Herrero et al. 1992). Another case is the group of ON stars, i.e. O-stars with N-enrichments (Walborn 1976, 1988; Howarth and Prinja 1989); this group contains many short-period binaries. An analysis of the association Per OB1 suggests (Maeder 1987b) that there may be a bifurcation in stellar evolution: while most stars follow the tracks of inhomogeneous evolution, a fraction of about 15%, mainly composed of fast rotators and binaries, may evolve homogeneously and become ON blue stragglers.

It was also suggested that there exists a mass discrepancy for OB-stars (cf. for example Herrero et al. 1992), in the sense that spectroscopy suggests that O-stars are overluminous for their masses. Langer (1993) has suggested that the overluminosity of O-stars results from rotational mixing enlarging the helium core. However, the situation is still not so clear and the claimed discrepancy might have been produced by unsafe modelling of stellar atmospheres. This view seems confirmed by the fact that more recent works by Pauldrach et al. (1994) do not find the mass discrepancy any more.

We retain as a very important result that fast rotators among OB stars generally present He and N enrichments, which is the sign of the transport of nuclearly processed elements.

3.2. Blue supergiants: He and N enhancements

Walborn (1976, 1988) has made the hypothesis that ordinary OB supergiants are enriched in helium and nitrogen and depleted in carbon, as a result of CNO processing. According to Walborn, the particular case may just be the small group of OBC supergiants, which have cosmic abundances (Howarth and Prinja 1989). In the line of the above hypothesis, Herrero et al. (1992) showed that supergiants of type Ia, Iab and Of stars present He enhancements. Like for all rules, there are exceptions: some B-supergiants do not show He and N excesses. Also, fast rotators of all luminosities present evidences of CNO processing. Similar enhancements of nitrogen and helium abundances have also been found for several post-MS B-type stars by Gies and Lambert (1992). Also, as expected, the so-called OBN stars show strong evidences of He and N excesses with C depletion (Walborn 1988).

Abundances determinations have also been made for B supergiants in the LMC and SMC, which is particularly interesting in relation with studies on the status of the progenitor of SN 1987 A. These supergiants generally show He and N enhancements (Lennon et al. 1991). A recent high dispersion study of LMC B-supergiants also confirms the general He and N-enrichments (Fitzpatrick and Bohannon 1993). Among 62 stars of types B0.7 to B3 only seven are OBC stars. These authors conclude, in agreement with Walborn's hypothesis, that it is the "typical" supergiants which show contaminated surfaces and that it is the rare N weak stars (OBC) which have retained their original main sequence surface abundances. The progenitor of SN 1987, which was a B-supergiant, had N/C and N/O ratios larger by respectively 37 and 12 than solar ratios (Fransson et al. 1989). From all these results it is clear that most B-type supergiants in the Galaxy, the LMC and the SMC generally show evidences of CNO processing.

The above observations place severe constraints on stellar models. These do not usually predict He and N enrichments in blue supergiants at solar composition. This is a real He discrepancy. At solar Z, blue loops with the associated He and N enrichments (as a result of dredge-up in red supergiants) only occur for $M \leq 15 M_{\odot}$. This is the case for the models with Schwarzschild's criterion and overshooting and with Ledoux's criterion. Models with semiconvection (Arnett 1991) have the same difficulty: at solar composition, the evolution goes straight to the red supergiants and there are no enriched blue supergiants. At lower metallicity, the blue loops are generally more developed and thus there are blue supergiants predicted which contain He and N enrichments. However, even in this case it seems necessary (Langer 1993) to advocate some rotational mixing to account for the observed enrichments.

Indeed, the study of CNO abundances in three A-type supergiants (Venn 1993) reveals N-enrichments larger than predicted by the first convective dredge-up, if these stars have firstly gone to the red supergiant stage. This supports the necessity of an additional mixing. The analyses of four F-type supergiants by Luck and Lambert (1985) also show materials processed by the CN cycle, at a level which may be higher than predicted. Analyses of some F and K supergiants in the SMC by Barbay et al. (1991) indicate solar N/Fe and C/Fe ratios, and thus no evidence of CNO processing. A further study by Barbay et al. (1992) of 14 galactic F-supergiants shows the absence of CNO processed material in stars with low rotational velocities. For F supergiants

with high rotation, the derivation of CNO abundances is unfortunately masked by the line broadening.

3.3. Constraints from SN 1987 A and supergiants

Several kinds of models have been proposed to account for the blue progenitor of SN 1987 A and its high N/C and N/O ratios.

- Models with low Z : These models spend their He-burning phase in the blue, where they generally also finish their life. However, they do not produce the observed red supergiants and N/C enhancements.
- Models with low Z and with mass loss may end their life in the blue as a result of mass loss only if the envelope mass is smaller than $1 M_{\odot}$, which is not supported by the interpretation of the light curve.
- Models with the Ledoux criterion for convection have been proposed by Woosley (1988) to account for the blue progenitor. However, when a moderate mass loss is taken into account, the final blue location occurs too early, i.e. during central He-burning, which is not in agreement with the suggestions that the precursor of SN 1987 A was a red supergiant a few thousand years before the explosion.
- Models with late mixing: The possibility of mixing of the external layers of a red supergiant at the end of the He-burning phase has been envisaged by Saio et al. (1988). Our models also confirm that at this stage the external and intermediate convective zones approach each other very closely so that any tiny convective extension is likely to bring them into touch. The resulting mixing produces simultaneously the He- and N/C-enrichment as well as the blue location of the SN progenitor, and this makes the suggestion by Saio et al. (1988) very attractive. In this case, standard models for the H- and He-burning are correct and extra mixing comes into play only in a very late stage. However, the physical mechanism responsible for the mixing has not yet been clarified.
- Models with semiconvection: they lead to a blue location of the supernova progenitor at $20 M_{\odot}$, which is very interesting with respect to SN 1987 A (Arnett 1991; Langer 1991). The physical connexion leading to the blue progenitor is most interesting (Langer 1991) and it illustrates quite a general stellar property. The mild mixing reduces the He-content in the He-burning shell, which is therefore less efficient. At the end of the He-phase, when the CO core contracts, the He-shell acts as a weak mirror and produces only a moderate expansion in the intershell region between the He and H shells. Thus, the H shell is not extinct and it stays very active. It acts as a strong mirror responding to the moderate intershell expansion by a strong contraction of the external envelope; the result is a blue final location. The models are quite interesting, however they do not account for the observed N/C and N/O ratios and some additional mixing mechanism may be necessary there. More meaningful would be the possibility that a unique physical mechanism account for the various observational constraints. However, this attractive possibility remains to be demonstrated.

A general major difficulty of all the existing models is that they produce no or nearly no red supergiants at low Z , while the observations for example in the young clusters of the Small Magellanic Cloud show the existence of numerous red supergiants. This is an important problem which has still to be solved.

3.4. Transition WN/WC stars

Among all WN stars, there are eight stars with inordinately strong CIV lines (Conti and Massey 1989). They were labeled WN/WC stars and suggested to be transition objects between WN and WC stars. Some mild mixing at the edge of the He core seems necessary to account for the existence of intermediate WN/WC stars (Langer 1991). These stars represent about 4% of the WR stars (Conti and Massey 1989), while models without extra-mixing only predict 1% or less of WN/WC stars. These stars cannot be explained by binary evolution. This shows that some additional mixing is necessary, but at the same time the small observed fraction of WN/WC stars implies that the part of the stellar mass which is actually mixed is relatively small, and this puts some limit on the role of mixing at the edge of the He-core.

4. Mass loss and the final evolutionary stages: the case for black hole formation

The heavy mass loss which leads to the very small final remnants illustrated in Fig. 1 considerably influences the chemical yields, the final stages and the nature of the final remnants. A particularly critical question concerns the value of the initial stellar mass M_{BH} above which black holes may form. Below, the evolution leads to neutron stars and white dwarfs. The value of M_{BH} is an essential property of stellar evolution and it is an essential parameter to determine the nucleosynthetic yields.

On the basis of a new soft equation of state including hyperons, Brown (1988) and Brown et al. (1992) have suggested a value of $1.5 M_{\odot}$ for the maximum mass of a neutron star. Current models for the birth of neutron stars show that, if after the bounce at nuclear densities the core is too large, the massive transient neutron star further collapses by general relativistic instabilities. The rest of the star is then accreted into the black hole within a few hours through a massive transient disk, so that little mass should be lost subsequently (A. Burrows, private communication). In this case collapse is direct, with no associated supernova nor ejected nucleosynthesis. For cores only slightly below the mass limit, an intermediate situation may occur, still with black hole formation and nevertheless a supernova explosion with some nucleosynthetic ejecta. There the collapse may be due to various mechanisms such as reverse shocks, rarefaction waves, etc... producing further accretion of matter on the core, leading to a central black hole. This scenario has been suggested (cf. Brown et al. 1992) to explain the apparent absence of a neutron star in SN 1987 A.

As said above, the final issue and the value of M_{BH} critically influence the nucleosynthetic production and in particular the yields from the onion skin layers of pre-supernova models. The ratio $\Delta Y/\Delta Z$ of the overall helium-to-metal enrichments is very sensitive (Schild and Maeder 1985) to the value of M_{BH} , since the production of heavy elements Z grows much more steeply with initial mass than does the helium production (Maeder 1992). The ratio $\Delta Y/\Delta Z$ is generally best determined from extragalactic HII regions, which span a wide range of metallicities Z . Recent analyses by Pagel et al. (1992) for low Z HII regions lead to values $\Delta Y/\Delta Z$ between 4 and 5, in agreement with other estimates.

The stellar models without black hole formation and swallowing of the onion skin layers (Arnett 1991) lead to a ratio $\Delta Y/\Delta Z$ of about 1 (see also model A at $Z = 0.001$ in Table 1). A hope was that the high mass loss rates known to exist in massive stars could explain the discrepancy. New grids of stellar models from 0.8 to 120 $M_{\odot}$ with various Z have been calculated with up-to-date ingredients and also including the positive dependence of mass loss rates on Z (Schaller et al. 1992). Indeed, at high Z , significant amounts of helium, and also of carbon, are ejected before being turned into heavier elements. Thus, mass loss increases the $\Delta Y/\Delta Z$ ratio. However, the observed mass loss rates lead to a maximum $\Delta Y/\Delta Z$ of about 2 (see model A at $Z = 0.02$ in Table 1), which is not enough.

Table 1 shows the ratio $\Delta Y/\Delta Z$ obtained (Maeder 1992) from new stellar models at $Z = 0.001$ and 0.020 integrated over the mass spectrum by Scalo (1986). Case A is the case without black holes (equivalent to $M_{\text{BH}} \simeq 120 M_{\odot}$): all remnants are taken equal to or smaller than 1.5 $M_{\odot}$. Other cases B, C, D and E are considered, corresponding to $M_{\text{BH}} = 27.5, 22.5, 17.5$ and 11.6 $M_{\odot}$. Above the limit M_{BH} we assume (see above) that no mass from the remaining onion layers escapes the collapse. Cases B, C, D, E correspond respectively to masses of the carbon-oxygen core of 8, 6, 4 and 2 $M_{\odot}$. Table 1 very clearly shows that in the case of no black holes (case A) the theoretical results are unable to reproduce the observed values of $\Delta Y/\Delta Z$ between 4 and 5 for low Z HII regions. The agreement is much better for models B-D, i.e. for M_{BH} around 20 $M_{\odot}$. This suggests that, at least at low Z , stars with initial masses larger than about 20 $M_{\odot}$ finish their life as black holes. This value of M_{BH} is much lower than the one of 40 to 80 $M_{\odot}$ proposed previously (van den Heuvel and Habets 1984; Schild and Maeder 1985).

Table 1. Relative enrichments of helium to heavy elements $\Delta Y/\Delta Z$ for models with $Z=0.001$ and $Z=0.020$ and for different lowest initial mass limits M_{BH} for black hole formation (Maeder 1992).

CASE	$M(\text{BH})$	$Z = 0.001$	$Z = 0.020$
A	120	1.34	2.07
B	27.5	4.32	2.30
C	22.5	5.30	2.61
D	17.5	7.32	3.11
E	11.6	19.38	4.01

We may collect some other indications also in favour of a low value of M_{BH} . The yields in heavy elements, especially in oxygen, are reduced by lowering M_{BH} down to 20 $M_{\odot}$; the reduction amounts to a factor 1.4 to 5.8 at $Z = 0.020$ or $Z = 0.001$. This allows us to reduce or solve the long-standing discrepancy of the oxygen overproduction by a factor of 2 to 3 (cf. Wheeler et al. 1989). Another indication comes from recent studies of explosive nucleosynthesis, which indicate a relative absence at low Z of r -process elements, like Eu. These elements should be created by massive stars. Low metallicity stars received, according to current models of chemical evolution, only

Fig. 2. The ratio $\Delta Y/\Delta Z$ of the enrichments in helium and heavy elements as a function of M_{BH} , the lowest initial mass for black hole formation. The curves for metallicities $Z = 0.001$ and 0.020 are shown. The horizontal hatched band shows the observed value $\Delta Y/\Delta Z$ by Pagel et al. (1992). On the top axis the values of the neutron star masses corresponding to the initial masses are given, according to Thielemann et al. (1993), the upper value is for prompt explosion, the lower for delayed explosion. The range corresponding to the upper mass limit of 1.5 $M_{\odot}$ for neutron stars is indicated by the vertical band. The various results converge towards a value of M_{BH} around 20 $M_{\odot}$.

nucleosynthetic contributions from the most massive stars. Thus, the relative absence of r -elements at low Z implies that there were little yields in r -elements from the most massive stars (Mathews and Cowan, 1990; Cowan et al. 1991). This supports the swallowing of onion skin layers in the process of core collapse.

Models predicting neutron star masses from supernova explosion by Thielemann et al. (1993) establish relations between the initial mass and neutron masses for two sets of assumptions (see Fig. 2, values on top of axis). Interestingly enough, there is a beautiful convergence of various constraints as illustrated by Fig. 2: the mass limit of about $1.5 M_{\odot}$ for neutron stars well corresponds to the value of the initial mass suggested by the study of the $\Delta Y/\Delta Z$ ratio, i.e. a value of M_{BH} around $20 M_{\odot}$.

Do all stars with initial masses above $20 M_{\odot}$ lead to black holes? The answer may depend on metallicity. Fig. 1 shows that, at low Z , due to the low mass loss, there is a monotonous relation between final and initial star masses; thus stars with $M > M_{\text{BH}}$ are likely to finish as black holes. At higher Z , like $Z = 0.020$, the relation is no longer monotonous (cf. Fig. 1). For initial masses larger than 30 or $40 M_{\odot}$, the final stellar masses are all very low with values around 5 to $10 M_{\odot}$ and have too small CO cores to likely form black holes. These low Wolf-Rayet masses are well supported by the study of the properties of these stars (Schaefer and Maeder 1992). Thus, at $Z = 0.020$, black holes may possibly form in a limited range of initial masses above M_{BH} , where the final masses are the largest ones. Above that range, neutron stars may again form. On the basis of the mass of the CO cores we find that in case C the range for black hole formation is about 22.5 to $30 M_{\odot}$, and 17.5 to $40 M_{\odot}$ in case D.

We may finally estimate the number of black holes in the Milky Way. With $M_{\text{BH}} = 20 M_{\odot}$ and the mass spectrum by Scalo (1986) the fraction of stars ending as black holes is $1.1 \cdot 10^{-3}$. If black holes occurred in the mass range 17.5 – $40 M_{\odot}$ (case D at $Z = 0.02$) or 22.5 – $30 M_{\odot}$ (case C), these fractions would then be $1.0 \cdot 10^{-3}$ and $3.3 \cdot 10^{-4}$ respectively. A typical fraction of 10^{-3} corresponds to about 200 million black holes in the Galaxy. This would represent about one third of the number of neutron stars, if they form above $8 M_{\odot}$.

I have made the above discussion of black hole formation to illustrate how such a basic physical process like mass loss by stellar winds may have far reaching consequences for other major astrophysical problems: even such a problem as mass loss may completely modify the occurrence of black holes in galaxies. This point is well in the spirit of this meeting on the role of physical processes in stellar evolution.

References

1. Arnett D., ApJ **383** 295 (1991)
2. Barbay B., Medeiros J.R., Maeder A., in Intl. Symp. on Nuclear Astroph., Karlsruhe, Ed. F. Käppeler, K. Wisshack, Institute of Physics Publ., Bristol and Philadelphia, p. 35 (1992)
3. Barbay B., Spite M., Spite F., Milone A., A&A **247** 15 (1991)
4. Brown G.E., Nature **336** 519 (1988)
5. Brown G.E., Bruenn S.W., Wheeler J.C., Comments Astrophys. **16** 153 (1992)
6. Chiosi C., Maeder A., Ann. Rev. Astron. Astrophys. **24** 329 (1986)
7. Conti P.S., Massey P., ApJ **337** 251 (1989)
8. Cowan J.J., Thielemann F.K., Truran J.W., Physics Reports **208** 267 (1991)
9. Fitzpatrick E.L., Bohannon B., ApJ **404** 734 (1993)
10. Fransson C., Cassatella A., Gilmozzi R., Kirshner R.P., Panagia N., Sonneborn G., Wamsteker W., ApJ **336** 429 (1989)
11. Gies D.R., Lambert D.L., ApJ **387** 673 (1992)
12. Herrero A., Kudritzki R.P., Vilchez J.M., Kunze D., Butler K., Haser S., A&A **261** 209 (1992)
13. Houdebine E.T., Foing B.H., Rodono M., A&A **238** 249 (1990)
14. Howarth I.D., Prinja R.K., ApJS **69** 527 (1989)
15. Kudritzki R.P., Pauldrach A., Puls J., A&A **173** 293 (1987)
16. Lamers H.J.G.L.M., Leitherer C., ApJ **412** 771 (1993)
17. Langer N., A&A **220** 135 (1989)
18. Langer N., A&A **252** 669 (1991)
19. Langer N., A&A **265** L17 (1993)
20. Leitherer C., Langer N., in IAU Symp. 148 "The Magellanic Clouds", eds. R.F. Hanes, D.K. Milne, Kluwer Acad. Publ. p. 480 (1991)
21. Lennon D.J., Kudritzki R.P., Becker S.T., Butler K., Eber F., Groth H.G., Kunze D., A&A **252** 498 (1991)
22. Luck R.E., Lambert D.L., ApJ **298** 782 (1985)
23. Maeder A., A&A **173** 247 (1987a)
24. Maeder A., A&A **178** 159 (1987b)
25. Maeder A., A&A **264** 105 (1992)
26. Maeder A., Conti P.S., Ann. Rev. Astron. Astrophys. in press (1994)
27. Mathews G.J., Cowan J.J., Nature **345** 491 (1990)
28. Meynet G., Maeder A., Schaller G., Schaefer D., Charbonnel C., A&AS **103** 97 (1994)
29. Mullan D.J., Doyle J.G., Redman R.O., Mathioudakis M., ApJ **397** 225 (1990)
30. Nieuwenhuijzen H., de Jager C., A&A **231** 134 (1990)
31. Pagel B.E.J., Terlevich R.J., Melnick J., Publ. Astron. Soc. Pacific **98** 1005 (1992)
32. Pauldrach A., Kudritzki R.P., Puls J., Butler K., Hunsinger J. A&A in press (1994)
33. Saio H., Kato M., Nomoto K., ApJ **331**, 388 (1988)
34. Scalo J.M., Fundamentals of Cosmic Physics **11** 1 (1986)
35. Schaefer D., Maeder A., A&A **263** 129 (1992)
36. Schaller G., Schaefer D., Meynet G., Maeder A., A&AS **96** 269 (1992)
37. Schatzman E., A&A **56** 211 (1977)
38. Schatzman E., A&A **279** 431 (1993)
39. Schatzman E., Maeder A., A&A **96** 1 (1981)
40. Schild R., Maeder A., A&A **143** L7–L10 (1985)
41. van den Heuvel E.P.J., Habets G.M.H.J., Nature **309**, 598 (1984)
42. Venn K.A., ApJ **414** 316 (1993)
43. Thielemann F.-K., Nomoto K., Hashimoto M., in "Origin and Evolution of the Elements" in honour of H. Reeves' 60th birthday. Eds. N. Prantzos, E. Vangioni-Flam, Cambridge Univ. Press (1993)
44. Walborn N., ApJ **205** 419 (1976)
45. Walborn N., in "Atmospheric Diagnostics of Stellar Evolution", IAU Coll. 108, Ed. K. Nomoto, Springer Verlag, p. 70 (1988)
46. Wheeler J.C., Sneden C., Truran J.W. jr., Ann. Rev. Astron. Astrophys. **27** 279 (1989)
47. Woosley S.E., ApJ **330** 218 (1988)
48. Zahn J.P., in "Astrophysical Processes in Upper MS Stars", 13th Saas-Fee Course, eds. B. Hauck and A. Maeder, Geneva Observatory, p. 253 (1983)
49. Zahn J.P., A&A **265** 115 (1992)