STELLAR EVOLUTION AND STELLAR POPULATIONS IN GALAXIES

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1 INTRODUCTION: FROM STAR PROPERTIES TO STELLAR POPULATIONS

Models of population synthesis are resting on an ensemble of other models, data and assumptions, in particular the models of stellar evolution, the data on initial compositions, the data on stellar spectra, the initial mass function (IMF), the star formation rate (SFR), the infall rate, etc... Here we shall concentrate on the properties of stellar models and their consequences for the global properties of stellar populations in galaxies.

The basic link between star properties and population synthesis is expressed in the so-called fuel consumption theorem (cf. Renzini and Buzzoni, 1986). It says that the contribution of stars in any post main sequence stage to the total luminosity of a star population is proportional to the amount of fuel burnt in the considered evolutionary stage. The demonstration of this theorem is rather straightforward. And although it is not used in recent population synthesis (cf. Guideroni and Rocca–Volmerange, 1987; Charlot and Bruzual, 1990), its didactical value is great. It shows how the integrated properties of star populations in galaxies directly depend on stellar internal properties. Indeed, the amount of fuel burnt in a given stage depends, in turn, on many physical assumptions in the models, such as the nuclear reaction rates, the opacities, convection and overshooting, mass loss, mixing processes, etc... Thanks to the above theorem, the effect of different model assumptions on population synthesis can be predicted, at least qualitatively.

2 THE NEED FOR A CHANGE IN ALL STELLAR MODELS

A few times per astronomer generation, stellar opacities are changing: 1955, 1970, 1977, 1991... This occurs just now again. The changes brought about by the new Livermore opacities (Iglesias and Rogers, 1991ab; Rogers and Iglesias, 1991) are quite large. The new opacities for metallicity $Z = 0.02$ are larger by a factor of 2–3 at log T = 5.5 compared to previous Los Alamos data. The results are well confirmed by independent works by Mihalas, Daeppen, Seaton and colleagues. Thus, it is not exaggerated to say that at the time of this writing, all existing models are obsolete and need to be reinvestigated.

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New complete grids with the new opacities and other up–to–date ingredients are now undertaken at Geneva Observatory for the mass range 0.8 to 120 $M_\odot$ and $Z = 0.02, 0.004$ and 0.001. From the first results by G. Schaller, we can mention the following changes: a slight decrease in luminosity and Teff by a few 10^{-2} dex, with a corresponding need to increase the solar helium content to Y = 0.30–0.31, a negligible reduction of the overshooting parameter. However, the main effect concerns the occurrence, duration and extension of the blue loops in the He–burning stage and a considerable widening of the main sequence band in massive stars. The many consequences of the opacity enhancements are now examined and will be analysed in coming works.

Apart from opacities, a very critical point in model computations is the extent of mixing by convective cores, since this extent directly determines the amount of fuel burnt. In absence of any reliable theory about overshooting the amount d_{over} of overshoot beyond the classical Schwarzschild limit is determined on the basis of observations (cf. Maeder and Mermilliod, 1981; Maeder and Meynet, 1989). The proposed value is $d_{over}/H_p = 0.25$, i.e. a modest value, much smaller than the very large overshooting applied by Bertelli et al. (1985) in their models and related investigations. As seen above, the overshooting parameter may undergo a small change due to the use of the new opacities. There are great differences in the locations of the main sequence envelope for various sets of models: VandenBerg (VdB, 1985), Yale (Y; Green et al., 1987), Bertelli et al. (BBC, 1985), Maeder and Meynet (MM, 1989). The VdB and Y models do not include overshooting, while the other two sets include it with different rates. There are also large age differences in the models. In that respect we must also emphasize that the MM models in the range 1.3 to 2.5 $M_\odot$ need to be corrected for a sizeable error in the time scales; the corrected values are available on request. Despite that fact, due to the account of overshooting or not, there remain appreciable differences in the age estimates.

Several mass limits are particularly critical for the models of population synthesis (cf. Renzini and Buzzoni, 1986; Charlot and Bruzual, 1990). As their values are greatly influenced by overshooting, let us examine the most significant mass limits.

- M_{HeF} is the maximum initial mass for degenerate He Ignition. The classical value is about 2.2 $M_\odot$ (cf. Becker and Iben, 1980); with moderate overshooting, we find it around 1.85 $M_\odot$, while Bertelli et al. (1985) found it at 1.6 $M_\odot$. Stars with $M < M_{HeF}$ develop a well populated red giant branch.

- M_W is the maximum initial mass leading to the formation of white dwarfs. The best estimates are observational and based on the presence of white dwarfs in clusters (cf. Weidemann, 1990), which lead to a value of about 8 $M_\odot$.

- M_{up} is the minimum initial mass for central C–burning. Below M_{up} there is no hydrostatic C–burning, stars form a degenerate C,O core surrounded by He– and H–burning shells and evolve as AGB stars. M_{up} is about 8.95 $M_\odot$ in models without overshooting (cf. Becker and Iben, 1980), while with moderate overshooting it is around 6.6 $M_\odot$; Bertelli et al. (1985) found 5.2 $M_\odot$ with large overshooting.

- M_{EC} is the maximum initial mass for stars undergoing core collapse by electron capture. Its value is around 10.2 $M_\odot$ (cf. Nomoto, 1984). It corresponds to no significant change for visible stages in the HR diagram, but only for the final event. Schematically one has the following mass intervals for models without overshooting:

	Red supergiants. Most nuclear burning is hydrostatic. Core collapse. Neutron star.
$M_{EC} = 10.2\ M_\odot$	
	Bright giants. Hydrostatic C–burning. e^- capture. Neutron star.
$M_{up} = 8.95\ M_\odot$	
	AGB stars. Degenerate core after He–burning. C–detonation. SN I 1/2. No remnant.
$M_W \simeq 8\ M_\odot$	
	AGB stars. Degenerate core after He–burning. Complete loss of envelope to form a white dwarf.
$M_{HeF} = 2.2\ M_\odot$	
	Red giant. He–flash, horizontal branch, AGB, white dwarf.

For models with overshooting, even moderate, the mass ranges are very different with large consequences for the mass interval of AGB stars, the appearance of a red giant branch and the nature of the final stages.

	Red supergiants. Most nuclear burning is hydrostatic. Core collapse. Neutron star.
$M_{EC} \simeq M_W = 8\ M_\odot$	
	Bright giants. Hydrostatic C–burning. Mass loss, large enough to form a white dwarf (likely C, O, Ne).
$M_{up} = 6.6\ M_\odot$	
	AGB stars. Degenerate core after He–burning. Complete loss of envelope to form a white dwarf.
$M_{HeF} = 1.85\ M_\odot$	
	Red giant. He–flash, horizontal branch, AGB, white dwarf.

Since AGB stars only appear below M_{up}, and RGB (red giant branch) stars below M_{HeF}, we notice that with overshooting AGB stars will turn on later during galactic evolution and the same for RGB stars. This has a large impact on the flux of galaxies, particularly in the near infrared. Also, with overshooting, the relative contribution of main sequence stars to

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the total flux is larger. Thus, overshooting is a critical problem for both stellar models and population synthesis.

3 MASSIVE STAR POPULATIONS IN GALAXIES

Due to their high luminosities, massive stars are observable in galaxies at large distances. As their lifetimes are short, they also are tracers of star formation. Particularly WR stars with their bright emission lines offer prominent signatures of starbursts in galaxies, even at very large distances. A most interesting case is that of the so-called WR galaxies, 40 of which are presently known (cf. Conti, 1991). Among the stellar properties showing very large differences from galaxy to galaxy and very large gradients in our Galaxy, the number frequencies of Wolf-Rayet stars present an extreme case. The number ratio of WR to O stars is larger by a factor of 10 in the Milky Way than in the Small Magellanic Cloud. Even more extreme, the number ratio WC/O of WC and O stars exhibits a difference of about two orders of a magnitude between the two galaxies. Some WR subtypes are totally missing in some galaxies, despite the fact that very young star populations are present. For example, there are no late WC stars in the LMC and SMC while there are many in the Milky Way.

The changes of Wolf-Rayet populations in galaxies with active star formation were first discovered in the pioneer work by Smith (1968, 1982). Further observational studies, particularly in the Magellanic Clouds by Breysacher (1981) and Azzopardi & Breysacher (1985), have confirmed the differences in the WR populations. Maeder et al. (1980) have proposed an explanation of the observed differences by a connection between the local metallicity Z and mass loss. The proposition by Maeder et al. was criticized by some authors who claimed that the galactic gradient in WR stars simply reflects the gradient in O stars. However, Meylan & Maeder (1983) showed that the galactic gradient of WR stars is steeper than the gradient of O stars. Thus the WR distribution in the Galaxy is not just a reflection of the O-star distribution and the WR gradient cannot be explained only by a change in the initial mass function.

Massive stars copiously evaporate during their evolution. Recent mass-loss rates for O-stars, supergiants and WR stars indicate that all stars with initial masses larger than 30 $M_{\odot}$ in Population I finish their life with final masses between 5 and 10 $M_{\odot}$ (cf. Maeder, 1990). Thus, it is not exaggerated to say that evaporation by stellar winds is the dominant factor in massive star evolution. In this context we immediately realize that a key point about massive star evolution in different galaxies is the relation between mass loss rates $\dot{M}$ and metallicity Z. If there were no such relation, massive star evolution would be about the same everywhere. However, recent models of stellar winds (cf. Kudritzki et al., 1987, 1991; Leitherer, 1991) have suggested the existence of a relation of the form $\dot{M} \sim Z^{\alpha}$, with $\alpha = 0.5 - 0.7$. In this way Z-effects enter massive star evolution. In the SMC, in blue compact galaxies or in elliptical galaxies at high redshift, Z is low and so are the mass-loss rates, while in the solar neighborhood Z is high and mass loss effects are substantial. This mass loss versus metallicity relation influences all the outputs of massive star evolution.

For Wolf-Rayet stars, which are essentially He-CO stars, the initial metallicity is not expected to have great consequences on the effective mass loss rates. Recent works have shown that the mass loss rates $\dot{M}$ of WR stars depend on their actual masses M with an exponent of about 2.5 (cf. Langer, 1989) when hydrogen is no longer present. Such a relation is also accounted for in recent models (cf. Maeder, 1990, 1991), which give the lifetimes t_{WR}

in the WR stage as a function of mass and Z. The clear trend is an increase of t_{WR} with initial mass and Z. Also, the minimum mass for WR formation is lower at higher Z. The lifetimes in the various phases can be used to derive relative number frequencies WR/O, WC/WR, WC/WN.

For a galaxy or a large galactic ring the assumption of a constant SFR over the last few 10^7y is reasonable. (For a single HII region, this would not be acceptable and aging effects are likely to intervene). For the IMF the standard Salpeter's law is taken. Table 1 shows the theoretical values of some number ratios as a function of metallicities. We notice the great increase of the relative numbers WR/O and WC/WN with the initial Z. Detailed comparisons with observations based on data by van der Hucht et al. (1988), Conti and Vacca (1991), Smith (1988), Arnault et al. (1989) show a very good agreement. This gives powerful support to the evolutionary models and to the idea that metallicity Z, through its effects on the mass loss rates $\dot{M}$ of O-stars and supergiants, is responsible for the enormous differences of the WR populations in galaxies with active star formation, which also has great consequences for the chemical evolution of galaxies, as shown below.

Table 1: Theoretical number ratios for WR stars

Z	WR/O	WC/WR	WC/WN
0.002	0.0032	0.057	0.061
0.005	0.0182	0.192	0.237
0.020	0.0752	0.640	1.784
0.040	0.1557	0.736	2.784

4 CHEMICAL EVOLUTION OF GALAXIES

The key effect in the interpretation of past chemical abundances rests on the fact that massive stars have small lifetimes. In the early phases of galactic evolution, only massive stars contribute to the chemical enrichment due to their short lifetimes. As time goes by, 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 generally considered as the major effect regarding the changes of stellar yields as a function of time (cf. Matteucci, 1991; Truran, 1991). One should, however, also take into account the fact that the chemical yields are changing with the initial Z and may in this way influence the picture of chemical evolution of galaxies. The previous results on WR statistics and their differences in galaxies are relevant, since the WR stage is the last observable stage of massive stars before supernova explosion. Mass loss in massive stars acts as nucleosynthesis in two main ways: 1) The direct enrichment by stellar winds. 2) The difference in the remnant mass left at the time of core collapse. Figs. 1 and 2 from Maeder (1992) show the mass fractions of various elements ejected in the winds (hatched areas) and in the final stages for the models at $Z = 0.02$ and $Z = 0.002$.

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From the figures, we can notice the following properties:

— 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 low Z values, especially at $Z = 0.002$, the situation is just opposite: we notice in Fig. 2, both in the winds and in SN ejecta, the huge yield in oxygen and the very small one in carbon.

— It is also visible from Figs. 1 and 2 that the final masses of initially massive stars with $Z \geq 0.02$ are considerably reduced by mass loss at the time of SN explosions. At $Z = 0.02$, all stars with initial mass larger than about 30 $M_\odot$ finish their life with small masses in the range of 5 to 10 $M_\odot$. For such masses, the nucleosynthetic yields in O, C and Z are derived from models by Woosley and Weaver (1986), Meynet (1990) and Thielemann et al. (1991), which all give very similar relations between these yields and the mass M_{CO} of the carbon–oxygen core. The small leftover masses contribute to a drastic reduction of the oxygen yields in high Z models.

— For low and intermediate mass stars, the stellar yields in helium are relatively small 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, the main result is that the nucleosynthesis of helium, carbon, oxygen, neon (a very special case) and heavy elements is a function strongly depending on both mass and Z.

Table 2 shows the corresponding net yields y_i in Z, He, C and O and the returned fraction R. All quantities have been integrated over a Salpeter's mass spectrum. We strongly emphasize that the exact values of the net yields very much depend on the masses adopted for the collapsed remnants (lower part of Figs. 1 and 2, based for lower mass stars as current data for white dwarfs, cf. Weidemann, 1990, and on a relation between residual baryon masses and M_{CO} for larger masses, cf. Woosley, 1986). It is not well known under which conditions the stellar cores collapse to black holes. This is nevertheless a very critical point because if a black hole is formed at SN explosion, all or most of the stellar mass may be taken by the collapsed remnant and does therefore not contribute to nucleosynthesis. This uncertainty affects all nucleosynthetic predictions, in the past as well as the present ones. In Table 2 the yields at low Z for stars with $M > 20$ $M_\odot$ are also given. These may be considered as representative of the yields for very early galactic evolution, since there only stars with lifetimes shorter than the galactic age may contribute to the chemical enrichments. Mass loss effects at $Z = 0.002$ are small and we expect that for lower Z values the mass loss rates are similarly negligible.

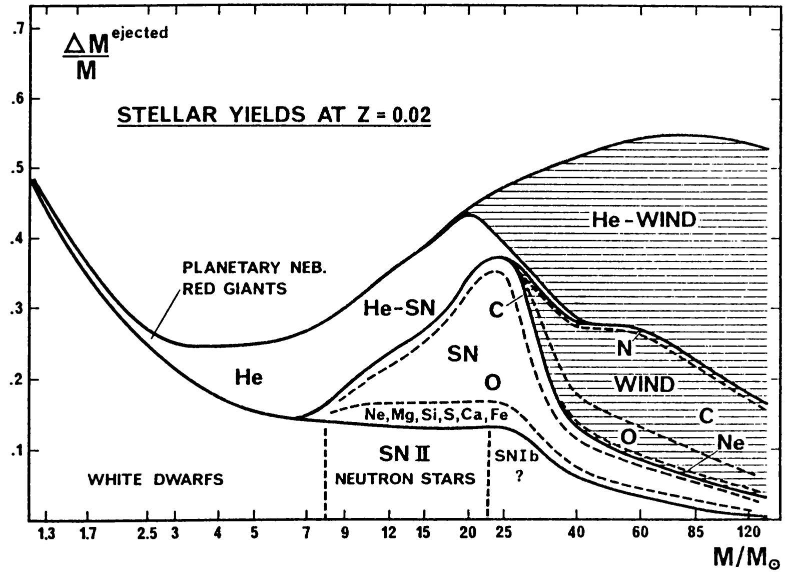

Figure 1 Mass fractions ejected as a function of initial masses for $Z = 0.02$.

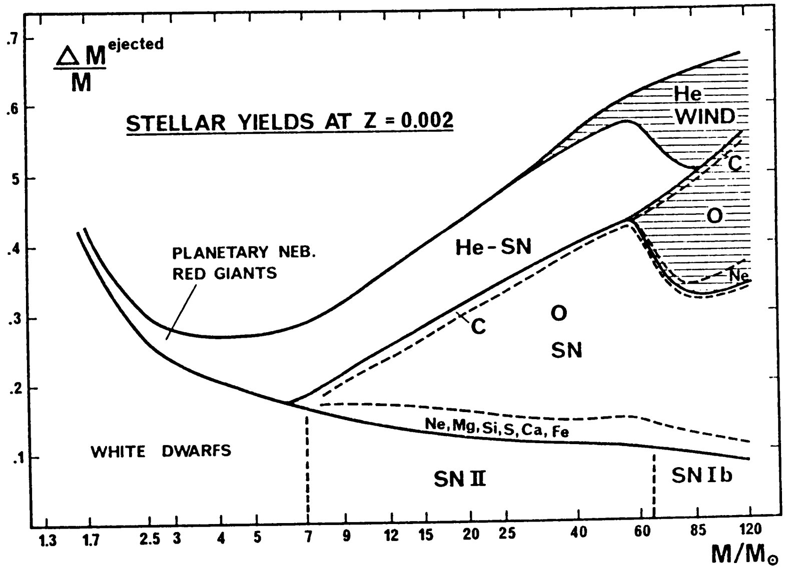

Figure 2 Mass fractions ejected as a function of initial masses for $Z = 0.002$.

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Table 2: Net yields in heavy elements Z, in helium, carbon and oxygen. R is the returned fraction.

Z initial	Z	He	C	O	R returned
1–120 $M_\odot$					
0.002	0.0191	0.0181	0.00090	0.0150	0.7656
0.005	0.0191	0.0171	0.00240	0.0144	0.7728
0.020	0.0141	0.0201	0.00465	0.0076	0.7770
0.040	0.0111	0.0162	0.00401	0.0050	0.8036
20–120 $M_\odot$					
0.002	0.0325	0.0155	0.00091	0.0276	0.8937

From Table 2 we notice that the yields in Z and O strongly decrease during galactic evolution, in agreement with recent results by Josey and Tayler (1991). Several authors (cf. Twarog and Wheeler, 1982, 1987; Larson, 1986; Matteucci, 1986; 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, 1986). 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. In this context, the models given above may be welcome. Models with no or low mass loss, like at $Z = 0.002$, predict very high net yields y_O in oxygen, while at $Z = 0.002$ or 0.04 the values of y_O are a factor 4 to 6 smaller. Thus, the present models imply that the oxygen production is much smaller during a large part of galactic evolution than predicted by constant mass models. This is such as to considerably alleviate the well known problem of the overproduction of oxygen.

Metal deficient stars in the Galaxy generally show an excess in the abundance ratio $[O/Fe]$. This trend, firstly found by Conti et al. (1967), is well illustrated in various plots, such as the plot of $[O/Fe]$ vs. $[O/H]$ by Wheeler et al. (1989). Thus, the present stellar models also exhibit the same trend.

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 originating from big bang nucleosynthesis (for recent references, see 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 (e.g. Peimbert and Torres Peimbert, 1974; Lequeux et al., 1979; Kunth and Sargent, 1983; Kunth, 1983; Pagel et al., 1986; Peimbert, 1986; Pagel, 1989, 1991).

The ratios of the yields from Table 2 are $y_Y/y_O = 3.26, 1.21, 0.56$ for the cases $Z = 0.04, 0.002$ and the case $Z = 0.002$, $M > 20\ M_\odot$ respectively. The ratios y_Y/y_Z are 1.46 at $Z = 0.04$ and 0.48 for $Z = 0.002$ with $M > 20\ M_\odot$. We notice that these theoretical values, although larger than most previous theoretical values, are smaller than some observed values, in particular that by Peimbert or by Pagel, who give a value of 3 or more. Among possible causes for the differences we must mention two main ones. Firstly, the contamination of HII regions by the winds of massive stars may be a problem. On the theoretical side, the uncertainty regarding the initial mass M_{BH} above which core collapse leads to a black hole is very critical. It is clear that if M_{BH} is equal to 60 $M_\odot$ or 25 $M_\odot$, the nucleosynthetic yields are very different, in particular the latter value leads to a much larger $\Delta Y/\Delta Z$ ratio. This is due to the fact that above M_{BH} the helium ejected in stellar winds contributes to galactic enrichment but not the heavy elements locked in the collapsed object. This problem was already discussed by Maeder (1984) and by Schild and Maeder (1985). From their data, a $dY/dZ = 3$ corresponds to a M_{BH} value around 20 $M_\odot$. However, the results about dY/dZ have ranged from 1 to 6 during the last decade, so it is perhaps premature to draw any firm conclusion about the value M_{BH}.

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