Chemical evolution models with a new stellar nucleosynthesis

A. Giovagnoli\(^1\) and M. Tosi \(^2\)

\(^1\)Dipartimento di Astronomia, Università di Bologna, via Zamboni 33, 40126 Bologna, Italy; \(^2\)Osservatorio Astronomico, via Zamboni 33, 40126 Bologna, Italy

Received ; in original form 1993 June 8

ABSTRACT
Numerical models for the chemical evolution of the Galaxy have been computed with the new stellar yields published by Maeder (1992). These metallicity dependent yields represent an important improvement in the chemical evolution of galaxies but there are still uncertainties in the stellar evolution which prevent completely satisfactory results. From the comparison of the model predictions with the corresponding observational constraints we find that Maeder's nucleosynthesis reproduces the oxygen and carbon abundances and provides consistent \(\Delta Y/\Delta(O/H)\) ratios if a significant amount of gas is accreted by the galactic disc during its whole lifetime. The lower mass limit for the black hole formation (\(M_{bh}\)) must be larger than 22.5 \(\text{M}_\odot\) to avoid oxygen underproduction.

Key words: Galaxy: evolution – Galaxy: chemical abundances – stellar nucleosynthesis.

1 INTRODUCTION
One of the major factors affecting the chemical evolution of galaxies is the production (or destruction) of the elements inside the stars. The successive pollution of the interstellar medium (ISM) due to the element ejection from their parent star, weighted with the proper stellar initial mass function (IMF) and coupled with the proper star formation rate (SFR), is in fact what produces the chemical abundances currently observed in any galaxy. It has actually been shown (Tosi 1988, Matteucci & François 1989) that the abundance ratios between different elements (e.g. N/O and O/Fe) or isotopes (e.g. \(^{12}\text{C}/^{13}\text{C}\)) depend mostly on the stellar nucleosynthesis and very little on galactic parameters like the star formation and infall rates if the accreted gas has chemical abundances in roughly solar proportions. Under these circumstances, the results of the computations on stellar evolution and nucleosynthesis are of primary importance to model the chemical evolution of galaxies, since they provide the amount of each element synthesized by stars of any initial mass and the relative time taken by each star to eject it in the ISM.

In the last fifteen years several important works (e.g. Arnett 1978, Chiosi & Caimmi 1979, Renzini & Voli 1981, Maeder 1981 and 1983, Woosley & Weaver 1986) have been devoted to stellar evolution models with detailed nucleosynthesis calculations of the most diffuse elements (\(^{4}\text{He},^{12}\text{C},^{14}\text{N},^{16}\text{O},\text{ etc})\). These studies have provided a grid of chemical yields generally considered reliable enough to be adopted in galactic evolution models. Despite the well known uncertainties on several stellar parameters (e.g. mixing length, mass loss, opacities) these yields have in fact proved roughly consistent with each other and with the corresponding observational constraints. Most of these stellar models, however, were computed only for the solar metallicity \(Z_\odot=0.02\), thus leaving room for some concern about the possibility of adopting their resulting yields also in epochs or in regions where the ambient metallicity is much different from \(Z_\odot\).

Maeder (1992, hereinafter M92) has recently examined this problem and presented the results of nucleosynthesis in stars with various initial metallicities. In addition, his stellar models are based on the most recent assumptions for all the input physics (i.e. overshooting from convective cores, opacities and mass loss). It is therefore of great interest to check what are the predictions of chemical evolution models adopting these new yields (see also Carigi 1994 and Prantzos 1994 for the evolution of the solar neighbourhood). To this aim, we have computed several numerical models of chemical evolution of the galactic disc assuming M92 new yields, and compared their results with those obtained with the models assuming the yields presented by previous authors and described in the next section.

In the next section we describe the model assumptions, indicating the major differences between the two sets of adopted yields. In Section 3 we compare the model predictions with the corresponding empirical data and in Section 4 we discuss the inferred conclusions.

\(\odot\) 0000 RAS
2 THE MODELS

The chemical evolution code employed here is described in detail in Tosi & Díaz (1985) and Tosi (1988). It accounts for the stellar lifetimes (i.e., avoids the instantaneous recycling approximation) and follows the stellar nucleosynthesis of several elements. The galactic disc is divided into concentric rings; radial gas flows between rings as well as infall of external gas onto each ring are allowed for. The star formation and the gas infall rates can vary with time and with galactocentric distance. The adopted age of the disc is $T=13$ Gyr (e.g. Twarog 1980).

The chemical evolution models have been computed with two alternative assumptions for the stellar nucleosynthesis: the standard values defined below and Maeder’s (1992) new results. In the latter case, to follow all M92 prescriptions also the stellar lifetimes, remnants and returned fractions have been changed accordingly to his new values. The nucleosynthesis results are given in tables 5 and 6 of M92 for two initial stellar metallicities, $Z=0.001$ and $Z=0.02$. We have then adopted the low metallicity yields from the disc formation up to the time when the ISM reaches the solar metallicity (an epoch different for different galactocentric distances) and the $Z=0.02$ values afterwards. The standard yields, instead, are complete only for solar metallicity models and we have therefore assumed their constant contribution throughout the disc lifetime.

2.1 Standard Yields

Hereinafter we will refer to the yields adopted by Díaz & Tosi (1986, hereinafter DT86) and Tosi (1988) as the standard yields. These values are derived from the nucleosynthesis computations by Renzini & Voli (1981) for low and intermediate mass stars and by Arnett (1978), revisited by Chiosi & Caimmi (1979), for massive stars. To take into account also the effect of massive star winds, the latter yields are combined with Maeder’s (1981, 1983) values. On this basis, the elements for which the evolution can be modeled are $^4$He, $^{12}$C, $^{13}$C, $^{14}$N and $^{16}$O. We recall that Renzini & Voli showed that during the envelope burning on the asymptotic giant branch of intermediate mass stars some primary $^{13}$C and $^{14}$N are produced. Thus, none of these five elements can be considered completely secondary (i.e. requiring a previous generation of stars to be synthesized). To resume the overall results of this standard nucleosynthesis: $^4$He is produced by stars of any initial mass, $^{12}$C by both high and intermediate mass stars, $^{13}$C and $^{14}$N by intermediate mass stars, and $^{16}$O by massive stars only.

As already discussed by DT86 and Tosi (1988), these yields suffer of several problems. For instance, the chemical evolution model presented below assume a mixing length parameter $\alpha=1.5$ in the stellar envelope (see Renzini & Voli 1981) and no overshooting from convective cores (i.e. $\lambda=0$) whereas, according to more recent views on this field, a more proper combination of these two parameters could be with a slightly smaller value for $\alpha$ or a slightly larger value for $\lambda$. The uncertainties on these values have relevant effects on the determination of the correct element abundances. In fact, a smaller $\alpha$ implies less nitrogen, due to a lower production of its primary component during the envelope burning in asymptotic giant branch stars, while a larger $\lambda$ implies more oxygen, which is produced in the cores of massive stars, and less nitrogen, because of the reduced size of the stellar envelopes where $^{14}$N is mostly synthesized (e.g. Greggio and Tosi 1986, but see also Serrano 1986). On the basis of the most recent stellar evolution theories it is also possible that the contribution of intermediate mass stars to the enrichment of $^{12}$C, $^{13}$C and $^{14}$N has been slightly overestimated (Renzini, private communication).

It is also worth mentioning that the $^{12}$C($\alpha, \gamma$)$^{16}$O reaction rate may be faster than assumed in these standard models, thus producing more oxygen and less carbon, and that the actual nucleosynthesis of $^{13}$C should be quite different to allow a galactic radial gradient of $^{12}$C/$^{13}$C as steep as that derived from molecular clouds observations (Tosi 1988, D’Antona & Matteucci 1991).

2.2 M92 New Yields

The standard yields were all computed for stellar models with initial solar composition. To overcome this limitation and to introduce the proper updating on several parameters, Maeder has recently computed a complete grid of stellar evolution tracks with different initial metallicity $Z$ and published (M92) the results of their nucleosynthesis for $Z=0.001$ and $Z=Z_\odot=0.02$. The major differences between his new models and the standard ones are the inclusion of a moderate ($\lambda \approx 0.2$) overshooting from convective cores, the adoption of new opacity tables (Roger & Iglesias 1992) and different evaluations of the stellar remnants after the wind mass loss and of the limiting mass for black hole formation. He also takes into account the dependence of the mass loss rate on metallicity and correctly assumes different initial helium content for different initial metallicity ($Y=0.243$ for $Z=0.001$ and $Y=0.30$ for $Z=0.02$).

The ranges of masses where $^4$He, $^{12}$C, $^{14}$N and $^{16}$O are produced are the same as in the standard nucleosynthesis. Since M92 stellar models for low and intermediate mass stars do not reach the final evolutionary phases, the corresponding heavy element contributions are not given in that paper and we take them from Renzini & Voli (1981).

An important conclusion of M92 is that the nucleosynthetic production strongly depends on the stellar initial metallicity $Z$. In particular: for increasing $Z$, $^{16}$O is strongly depleted, $^{12}$C is highly enhanced in stars more massive than 25 $M_\odot$ but fairly reduced in smaller stars, and $^4$He is highly enhanced in very massive stars and roughly constant in the others.

If we compare the amount of each of these elements ejected by massive stars in M92 models for $Z=0.02$ with the corresponding amount in standard models (see also Figs 7 to 10 in M92), we find that in M92 the $^4$He enrichment is larger, $^{12}$C is much larger for very massive stars, $^{16}$O is slightly larger for $10 \leq M/M_\odot \leq 25$ and much smaller for more massive stars. For $Z=0.001$, M92’s ejected masses are similar to the standard ones with $Z=0.02$ for $^4$He, lower for $^{12}$C and slightly larger for $^{16}$O. The total metallicity $Z$ produced by massive stars is fairly lower than the standard value for $Z=0.02$ and only slightly lower for $Z=0.001$. © 0000 RAS, MNRAS 000, 1–6.
The predictions of chemical evolution models for our galactic disc based on standard nucleosynthesis have been compared by Tosi (1988) with the corresponding observational data. Here we simply recall the results more relevant to our current issue and show only the predictions of one of the models in better agreement with all the observational constraints. From now on this model will be referred to as the standard model; it assumes an exponentially decreasing SFR with e-folding time $\tau=15$ Gyr and initial value derived from the observed amount of current gas and total mass in each ring, an almost constant infall rate after the disc formation with uniform density across the entire disc of $4 \times 10^{-5} M_\odot kpc^{-2} yr^{-1}$, and Tinsley’s (1980) IMF.

The radial gradients of the nitrogen and oxygen abundances derived from HII region observations (Peimbert 1979, Shaver et al. 1983) are very well reproduced by the standard model. As for the absolute values of their abundances, the predicted oxygen content is in good agreement with the data (Fig. 1, where the standard model is represented by the thick solid line), whereas a value of the mixing length parameter $\alpha$ intermediate between those available in the literature ($\alpha=1.0$ and $\alpha=1.5$) would be required to achieve the same agreement for nitrogen. In fact, too much $^{14}$N is produced if $\alpha=1.5$, but its resulting abundance is too low if $\alpha=1.0$ (see DT86, fig.4). Similarly, an intermediate value of $\alpha$, say $\sim 1.2$, would allow to reproduce both the trend and the absolute values of the N/C ratio with C/H as derived by Laird (1985) from the spectroscopy of more than a hundred stars in the solar neighbourhood (see DT86, fig.7).

The predicted distribution with time of the overall metallicity in the solar ring is in agreement with Twarog’s (1980) age-metallicity relation (thick solid line in Fig. 2) except for the very early epochs after the disc formation where the model predicts too low metallicities because it assumes an initial $Z=0$. We emphasize that Twarog’s $[\text{Fe/H}]$ is not the iron abundance but represents the global metallicity normalized to its solar value.

To allow for an immediate comprehension of what is the effect of assuming M92 stellar nucleosynthesis, the thin solid line in Figs 1 to 4 shows the predictions of a model (model 1) with all the parameters (namely: IMF, SFR and infall rate) identical to those of the standard model. As already mentioned in the previous section, we adopt the $Z=0.001$ nucleosynthesis provided by M92 up to the epoch when the ISM reaches $Z=0.02$ and its solar nucleosynthesis afterwards.

Model 1 reproduces well the observational properties of our Galaxy. At the present epoch it predicts oxygen abundances in the ISM of the whole disc in good agreement with the observational data (HII regions) and with the standard model (thin solid line in Fig. 1). The divergence of the solid lines at the outermost ring is due to the differences between the $Z=0.001$ and $Z=0.02$ oxygen yields. The former are higher than the latter and since the outer ring reaches the solar metallicity much later than the others, it is enriched...
Figure 3. Fraction of G-dwarf stars in the solar neighbourhood as a function of their oxygen abundance. The histogram corresponds to Pagel’s (1989) observational data; the model symbols are as in Fig.1.

for longer times by the higher O-yields. For this reason it shows at the present time higher oxygen abundances.

The frequency distribution with [O/H] of the G-dwarfs in the solar ring predicted by model 1 looks consistent with the data (thin solid line in Fig.3a), although model 1 predicts too many G-dwarfs with low oxygen.

Fig.4 shows the model results for the radial distribution of $^{12}\text{C}$. These predictions can be compared with the corresponding observational data available for the solar neighbourhood. The vertical line in Fig.4 represents the range of carbon abundances derived by Laird (1985) from the spectroscopy of 116 nearby stars and its length includes both his quoted observational error ($\pm 0.25$ dex) and the abundance spread probably due to the different ages and/or initial metallicity of the examined stars. As usual, the thick solid curve in this figure represents the predictions of the standard model, whereas the thin solid line corresponds to the analogous model 1 with M92 nucleosynthesis. The standard predicted abundances fall within the observed range as well as those based on M92 but the latter show a rapid decrease in the outer regions of the disc. Since the carbon contribution from low and intermediate mass stars is the same as that of the standard model (i.e. that from Renzini & Voli 1981), we infer that the higher abundances at inner radii and the rapid decrease in the outer ones are due to the yields of M92 massive stars that produce more carbon at $Z=Z_\odot$. Despite their larger values, we find that the carbon abundances predicted by the combination of Maeder’s massive stars yields with those from intermediate mass stars are consistent with the observed data contrary to what is suggested by Prantzos et al. (1994).

The age-metallicity relation predicted by model 1 is roughly consistent with the corresponding observational data (Fig. 2) and does not differ significantly from the predictions of the standard model.

Figure 4. Carbon abundance distribution in the galactic disc. The vertical line corresponds to the range of values derived by Laird (1985) from observations of stars in the solar neighbourhood. The model symbols are as in Fig.1.

We have computed other numerical models with various choices of the evolutionary parameters SFR, IMF and infall, and covering as much as possible the range of reasonable values of these parameters. Table 1 lists the most significant of these models, which are described in this paper.

One of the most controversial issue in galaxy evolution concerns the presence of infall of gas on spiral galaxies. The only observational evidence of infall are High Velocity Clouds (HVC’s) and mostly Very High Velocity Cloud’s. In order to check the role of infall in the chemical evolution based on M92 yields we have assumed no accretion after the disc formation (model 2), thus removing any dilution of the ISM. The dotted line in Fig.1 shows that the oxygen predictions of model 2 do not reproduce the observational data, even if the oxygen depletion with increasing $Z$ makes the disagreement less dramatic than with standard nucleosynthesis. As often found for no infall model, the slope of the abundance gradient is not reproduced either. Fig. 4 shows that also the carbon predicted abundance is inconsistent with the observational constraint in the solar neighbourhood. As for the metallicity distribution of the G-dwarfs (Fig.3a), this closed box model predicts as usual more stars with low $[\text{O/H}]$. This is because the disc does not accrete mass during its life and starts forming stars already with its final mass. Thus, a larger number of stars are formed at early epochs, and therefore with low initial metallicity, than in models with infall. For the same reason, the age-metallicity relation (dotted line in Fig.2) shows lower abundances at early epochs. It also shows too large abundances at recent epochs, due to the lack of any dilution of the ISM enrichment. It is then clear that removing infall worsens the predicted stellar metallicity distribution. Intermediate values of infall obviously provide intermediate results and we therefore conclude that even with metallicity dependent yields the amount of accreted gas must be around $B = 4 \cdot 10^{-3} M_\odot kpc^{-2} yr^{-1}$ as found with constant yields.

In model 3 we have adopted Salpeter’s IMF instead of Tinsley’s. Salpeter’s mass function assumes a larger frac-
tion of massive stars because the exponent for that mass range is -2.35 instead of Tinsley’s -3.3, and this increases the amount of oxygen available at the end of the Galaxy evolution, since this element is produced only by high mass stars. Model 3 (short-dashed line in all figures) assumes an infall rate of $4 \times 10^{-3} M_\odot kpc^{-2} yr^{-1}$ and the only difference with model 1 resides in the IMF. The oxygen distribution predicted by model 3 is shown in Fig. 1 where the oxygen overproduction due to the larger fraction of massive stars is apparent. The age-metallicity relation (Fig. 2) is in agreement with the observational constraints while the carbon predicted distribution (Fig.4) is completely out of the data range. This inconsistency is due to the larger carbon production by massive stars with $Z=0.02$ combined with Salpeter’s larger fraction of massive stars. Model 3 predicts many G-dwarfs (Fig. 3b) with “solar” oxygen abundance because it produces oxygen faster than model 1 and therefore reaches the solar abundance earlier.

Models with the star formation simply proportional to the gas density show by definition a radial distribution of the current SFR equal to that of the observed gas density and therefore too flat with respect to that derived from observations of recently formed objects (see e.g. Lacey & Fall 1985, Tosi 1988). Nonetheless, since this parametrization is still fairly popular we present their predictions for sake of completeness. A typical example of this class is model 4 (long-dashed lines in all figures) which assumes Tinsley’s IMF and an infall rate of $2 \times 10^{-3} M_\odot kpc^{-2} yr^{-1}$, a value quite lower than that required by the models discussed above with a different star formation law. This is because, in this case, the effect of infall is not simply to dilute the ISM abundances but also to increase the region gas density thus enhancing the SFR and the ISM chemical enrichment. Due to the different balancing between SFR and infall, the predicted oxygen (Fig.1) and carbon (Fig.4) abundances are fairly larger than with model 1. In the case of oxygen the curve predicted by model 4 still lies well within the observed range of abundances, but for carbon it is at the upper edge of the data. The large star formation activity occurred in this model at early epochs when most of the gas was available generates in the solar ring a large number of G-dwarfs with low oxygen content, and the low activity of more recent epochs, when less gas is available, generates only few stars with solar oxygen. These features make the G-dwarf distribution inconsistent with the empirical histogram of Fig.3b.

Finally, we have examined the effect of assuming an upper mass limit for the stellar contribution to the ISM, $M_{bh}$. All the stars with initial mass higher than $M_{bh}$ collapse into a black hole and do not contribute to the ISM enrichment with a final explosion. In M92 various limiting masses $M_{bh}$ for black hole formation are considered. Considering Maeder’s arguments and bearing in mind that the supernova (SN 1987A) recently exploded in the Large Magellanic Cloud originated from a 20$M_\odot$ star, the lowest reasonable choice for $M_{bh}$ seems be $22.5 M_\odot$ (M92 case c). In Figs 1 and 4 (short-dash-dotted line) we present the corresponding effect on the predictions of model 1. From these two figures one can see that the decrease in oxygen is much stronger than in carbon because of the different mass range where these elements are mostly produced. This choice of $M_{bh}$ cuts significantly the range of masses contributing to the oxygen enrichment and leads to current abundances totally inconsistent with the data. The age-metallicity relation is not affected by the $M_{bh}$ introduction whereas the G-dwarf distribution (Fig. 3a) predicts too many stars at low oxygen abundances and it does not reproduce the “solar” observational value. It is then unacceptable, as a priori obvious and already found by Maeder.

As further check we have applied the same limit $M_{bh}=22.5 M_\odot$ to model 3 which was found to predict too large oxygen abundances because of the large fraction of massive stars. Model 6 (long-dash-dotted line in all figures) has then been calculated as model 3 but with the introduction of the mass limit for black hole formation. As expected the oxygen abundance is sensibly depleted and is now roughly consistent with the observational data. Carbon however is not reduced enough and remains well above the observation range. The G-dwarfs distribution (Fig. 3b) is not satisfactory either.

### 4 DISCUSSION

In the previous section we have compared the model predictions on the C and O abundances based on Maeder’s (1992) nucleosynthesis with the corresponding values observed in the Galaxy. It is clear that the strong metallicity dependence of M92 nucleosynthesis affects the chemical evolution results. For instances, models 1, 4 and 5 show a particular behaviour in the outer regions of the disc where the lower metallicity yields are used for most of the galactic life. On the other hand some of the general results derived (e.g. Tosi 1988) with the classical nucleosynthetic prescriptions are still valid with M92 yields. Models without infall (e.g. model 2) must be rejected because they do not allow to reproduce either the G-dwarfs distribution or the O and C abundances. Different choices of SFR (model 4) and IMF (model 3) generally worsen the agreement between theoretical predictions and observational constraints.

An interesting effect of metallicity dependent yields is on the helium-metallicity relation $\Delta Y/\Delta Z$ which has important cosmological implications since it provides, by extrapolation to $Z=0$, the primordial value of $^4$He. Up to date, there are no direct estimates of the true $\Delta Y/\Delta Z$. What is actually observed is not the global metallicity but oxygen (mostly in galactic and extragalactic HII regions) and the empirical $\Delta Y/\Delta Z$ is derived from its abundances assuming a linear correlation between $Z$ and $O$. This correlation is ex-

### Table 1. Models with M92 nucleosynthesis

| Model | SFR  | Infall | IMF       |
|-------|------|--------|-----------|
|       | $\tau = 15$ Gyr | $B = 4 \cdot 10^{-3}$ | Tinsley   |
| 2     | $\tau = 15$ Gyr | $B = 0$        | Tinsley   |
| 3     | $\tau = 15$ Gyr | $B = 4 \cdot 10^{-3}$ | Salpeter  |
| 4$^\dagger$ | $2 \cdot 10^{-3}$ | $Tinsley$   |
| 5$^\dagger$ | $2 \cdot 10^{-3}$ | $Tinsley$   |
| 6$^\dagger$ | $2 \cdot 10^{-3}$ | $Salpeter$  |

$^\dagger$ Models 1 and 5 differ only in the black hole mass limit. The same applies to models 3 and 6.
tremely controversial: first of all because, as shown by M92 models, it is not actually linear, and second because different authors assume rather different slopes. To overcome these large uncertainties, and for a correct comparison of the model predictions with the corresponding observational data, we have chosen to examine the $\Delta Y/\Delta(O/H)$ resulting from the models because the empirical estimates of this ratio are directly derived from observations. The most updated and reliable value is provided by Pagel’s et al. (1992) from a large sample of H II regions in spiral and irregular galaxies, $\Delta Y/\Delta(O/H) = 125 \pm 40$. The values predicted by our chemical evolution models based on standard and on M92 nucleosynthesis are 63 and $\sim 72$, respectively. If we take into account the fact that the observational data refer mostly to metal poor galaxies and that some authors (e.g. Campbell 1992, Lenzuni & Panagia 1993) suggest that the ratio is lower in high metallicity objects (but see also Pagel 1993), we see that the standard and M92 values may both be roughly consistent with the empirical ratio. It is worth noticing that using the true Z abundance M92 finds $\Delta Y/\Delta Z = 3 - 6$ and out standard model gives $\Delta Y/\Delta Z = 3$ which is the ratio traditionally derived from observatons of spiral galaxies (e.g Lequeux et al. 1979, Torres- Peimbert, Peimbert & Fierro 1989 and references therein). Following M92’s suggestion, we have also checked the effect on the chemical evolution of the galactic disc of assuming an upper limit to the mass of the stars contributing to the ISM enrichment. We confirm that this limit cannot be very low ($M_{ bh} = 22.5$ $M_{\odot}$ is already too low) as already suggested by M92 and Prantzos 1994.

We believe that for a more detailed analysis of the mass limit in better agreement with the observed chemical features of the Galaxy, we should wait for update calculations of the stellar nucleosynthesis not only of massive stars. In fact, the major observational constraints involve elements like helium, carbon, nitrogen and iron which are mostly produced by stars smaller than those examined by M92. A revision of the classical work by Renzini and Voli (1981) with the most updated input physics would be necessary to achieve more significant results.

Acknowledgements We warmly thank Laura Greggio, Alvio Renzini and Claudio Ritossa for useful conversations on the stellar evolution models and Francesca Matteucci for interesting comments and discussions. We are grateful to André Maeder for a nice and lively discussion which has helped us to better understand the problem and to significantly improve the paper.

REFERENCES

Arnett W.D., 1978, ApJ, 219, 1008
Campbell A., 1992, ApJ., 401, 157
Cariţi, L., 1994, ApJ., 424, 181
Chiosi,C. & Caimmi,R., 1979, A&A, 80, 234
D’Antona, F. & Matteucci, F., 1991, A&A, 248, 62
Díaz,A.I. & Tosi,M., 1986, A&A, 158, 60, DT86
Greggio, L. & Tosi, M., 1986, A&A, 156, L1
Lacey, C.G. & Fall, S.M., 1985, ApJ, 290, 154
Laird, J.B., 1985, ApJ, 289, 556
Lenzuni, P. & Panagia, N., 1993, ApJ in press

Lequeux, J., Peimbert, M., Rayo, J.F., Serrano, A., Torres-Peimbert, S., 1979, A&A, 80, 155
Maeder, A., 1981, A&A, 102, 401
Maeder, A., 1983, A&A, 120, 113
Maeder, A., 1992, A&A, 264, 105
Marconi, G., Matteucci, F., Tosi, M., 1993, MNRAS, submitted
Matteucci, F., 1986, ApJ, 305, L81
Matteucci, F. & François, P., 1989, MNRAS, 239, 885
Matteucci, F. & Tosi, M., 1985, MNRAS, 217, 391
Pagel, B.E.J., 1989, in Beckman, J., Pagel, B.E.J. eds. Evolutionary Phenomena in Galaxies, p. 201
Pagel, B.E.J., 1993, in Alloin. D., Stasinska, G. eds. The Feedback of Chemical Evolution on the Stellar Content of Galaxies (Paris Obs. France), p.87
Pagel, B.E.J. & Patchett, B.E. 1975, MNRAS, 172, 13
Pagel, B.E.J., Simonson, E.A., Terlevich, R.J., Edmunds, M.G., 1992, MNRAS, 255, 325
Peimbert, M., 1979, in W.B. Burton ed. The Large Scale Characteristics of the Galaxy (Reidel, Dordrecht), p.307
Prantzos, N., 1994, A&A, 284, 477
Prantzos, N., Vangioni-Flam, E., Chaveau, S., 1994, A&A, 285, 132
Renzini, A., Greggio, L., Ritossa, C., Ferrario, L., 1992, ApJ, 400, 280
Renzini, A. & Voli, M. 1981, A&A, 94, 175
Rogers, F.J. & Iglesias, C.A. 1992, ApJ, 79, 507
Serrano, P.G., 1986, MNRAS, 98, 1066
Shaver, P.A., McGe, R.X., Newton, L.M., Danks, A.C., Pottasch, S.R., 1983, MNRAS, 204, 53
Tinsley, B.M., 1980, Fund. Cosmic Phys., 5, 287
Torres-Peimbert, S., Peimbert, M., Fierro, J., 1989, ApJ, 345, 186
Tosi, M., 1988, A&A, 197, 33
Tosi, M. & Díaz, A.I., 1985, MNRAS, 217, 571
Twarog, B.A., 1980, ApJ, 242, 242
Woosley, S.E., Weaver,T.,1986, ARA&A, 24, 205

This paper has been produced using the Royal Astronomical Society/Blackwell Science \LaTeX{} style file.