The evolution of the mass–metallicity relation in SDSS galaxies uncovered by astropaleontology

N. Vale Asari,[1,2]⋆ G. Stasińska,[2] R. Cid Fernandes,[1] J. M. Gomes[1,3] M. Schlickmann,[1] A. Mateus[4] and W. Schoenell[1] (the SEAGal collaboration)†

[1]*Departamento de Física - CFM - Universidade Federal de Santa Catarina, Florianópolis, SC, Brazil*
[2]*LUTH, Observatoire de Paris, CNRS, Université Paris Diderot; Place Jules Janssen 92190 Meudon, France*
[3]*GEPI, Observatoire de Paris, CNRS, Université Paris Diderot; Place Jules Janssen 92190 Meudon, France*
[4]*Instituto de Astronomia, Geofísica e Ciências Atmosféricas, Universidade de São Paulo, São Paulo, SP, Brazil*

ABSTRACT

We have obtained the mass–metallicity (M–Z) relation at different lookback times for the *same set of galaxies* from the Sloan Digital Sky Survey, using the stellar metallicities estimated with our spectral synthesis code STARLIGHT. We have found that this relation steepens and spans a wider range in both mass and metallicity at higher redshifts. We have modelled the time evolution of stellar metallicity with a closed-box chemical evolution model, for galaxies of different types and masses. Our results suggest that the M–Z relation for galaxies with present-day stellar masses down to 10^{10} M$_\odot$ is mainly driven by the history of star formation and not by inflows or outflows.

Key words: galaxies: evolution – galaxies: statistics – galaxies: stellar content.

1 INTRODUCTION

Since the study by Lequeux et al. (1979), who found a luminosity–metallicity relation for irregular galaxies, many papers have reported the existence of a luminosity–metallicity or mass–metallicity (M–Z) relation for all kinds of galaxies: The more massive galaxies are also the ones with more metal-rich interstellar medium (ISM).

Considerable work has also been devoted to explaining the M–Z relation. For instance, Tremonti et al. (2004) find that outflows play an important role in shaping the M–Z relation, as the weaker gravitation potential well of less massive galaxies makes them more prone to lose enriched gas via galactic winds or supernovae explosions. Finlator & Davé (2008) claim that inflows of pristine gas could also be a sound explanation, as the same amount of gas falling into galaxies would have a greater impact on the chemical composition of less massive ones. Köppen, Weidner & Kroupa (2007) advocate the role of an *integrated* initial mass function: massive galaxies comprise more massive clusters which may contain more massive stars that enrich the ISM faster.

The M–Z relation derived from emission lines has been found to change with redshift (Savaglio et al. 2005; Maiolino et al. 2008). The comparison between M–Z at low and high redshifts is, however, not straightforward. Different populations of galaxies live at different redshifts, and this alone can affect the derivation of the nebular metallicity, even if one were to apply the same calibrations for both

samples (see Stasińska 2008). Nevertheless, at least qualitatively, the observed results are in agreement with what is expected for the evolution of galaxies.

This brings us to another concern in M–Z studies: the bias in the derivation of the nebular metallicity from emission lines. The evolution of the M–Z relation is usually studied in terms of the abundance of oxygen in the ISM gas. As it is known (see e.g. Kewley & Ellison 2008), the measurement of nebular abundances is very dependent on the method and calibrations used.

With our stellar population synthesis code STARLIGHT, we can determine the stellar metallicities, $Z_\star$, and the total masses in stars, $M_\star$, at different epochs for any given galaxy (Cid Fernandes et al. 2007). We can thus follow the evolution of the M–Z relation *for the same set of galaxies* at different redshifts. Panter et al. (2008) used similar techniques and discussed the nebular metallicities with respect to stellar metallicities. In this study, we rely on stellar metallicities alone because, although they have their own problems, they are free from the biases affecting nebular abundance determinations. The use of $Z_\star$ also allows us to explore more massive galaxies, for which the nebular metallicity estimates are not possible, such as AGN hosts and galaxies which have stopped forming stars.

Since STARLIGHT allows the determination of the star formation histories (SFHs), we can go one step further and construct a simple chemical evolution model using these SFHs and see under what conditions it reproduces the observed time evolution of $Z_\star$. Savaglio et al. (2005) made a similar study, but using a theoretical SFH with e-folding time, related to galaxy mass, and for nebular metallicity instead of $Z_\star$. Here, we use the SFH obtained *directly* for each galaxy.

⋆E-mail: natalia@astro.ufsc.br
†Semi-Empirical Analysis of Galaxies

2 DATA

Our parent sample is composed of all objects spectroscopically classified as galaxies from Fifth Data Release of the Sloan Digital Sky Survey (SDSS) (Adelman-McCarthy et al. 2007). We exclude duplicate observations, and impose the following selection criteria: $14.5 \leq m_r \leq 17.77$ (from the Main Galaxy Sample definition), z-band aperture covering factor >20 per cent (to reduce aperture effects and avoid intragalactic sources), $S/N \geq 10$ at 4750 Å (to provide reasonable stellar population fits) and a narrow range in redshift $|z - 0.1| < 0.015$ (to be able to transform stellar ages into redshift in a simple way). The central redshift of 0.1 was chosen to maximize the number of objects and thus ensure reliable statistics over the whole range of ages considered in the analysis. We adopt a $H_0 = 70 \, \text{km} \, \text{s}^{-1} \, \text{Mpc}^{-1}$, $\Omega_M = 0.3$ and $\Omega_\Lambda = 0.7$ cosmology where appropriate. There are 82662 objects in the resulting sample.

We use the same data processing as outlined in Cid Fernandes et al. (2005) and Mateus et al. (2006). Our code STARLIGHT recovers the stellar population content of a galaxy by fitting a pixel-by-pixel model to the spectral continuum. This model is a linear combination of 150 simple stellar populations (SSP) extracted from Bruzual & Charlot (2003, hereafter BC03) with ages $1 \, \text{Myr} \leq t_\star \leq 18 \, \text{Gyr}$, and metallicities $0.005 \leq Z/Z_\odot \leq 2.5$, as in Cid Fernandes et al. (2007). Emission lines are then measured in the residual spectra, which reduce the contamination by stellar absorption features.

We divide our parent sample into three subsamples: star-forming (SF), retired (R) and Seyfert (S) galaxies. For both the SF and S samples, we select objects with $S/N > 3$ in the [O III]λ5007, Hβ, [N II]λ6584 and Hα emission lines, i.e. all the lines involved in the Baldwin, Phillips & Terlevich (1981, BPT) diagram. The SF sample is composed by the objects below the line proposed by Stasińska et al. (2006) to separate SF galaxies from AGN hosts. The S sample is defined as the galaxies with $\log([\text{N II}]/\text{H}\alpha) > -0.3$ and above the line defined by Schlickmann (2008) in the BPT diagram to separate S galaxies from low-ionization nuclear emission region (LINER)-like galaxies: $\log([\text{O III}]/\text{H}\beta) = 0.90 \log([\text{N II}]/\text{H}\alpha) + 0.48$.

The R sample is composed of galaxies with little evidence of either nuclear or SF activity, which includes passive galaxies, galaxies with very weak emission lines and even some which would be traditionally classified as LINERs (see Stasińska et al. 2008). Therefore, we impose the following cuts for the R sample: $S/N < 3$ in the 4 BPT lines and [O II]λ3727 ('passive'); or $S/N < 3$ in [O III] and/or Hβ, but $S/N \geq 3$ in [N II] and Hα, and $\log([\text{N II}]/\text{H}\alpha) > -0.15$ ('weak emission lines'); or $S/N > 3$ in the 4 BPT lines, $\log([\text{N II}]/\text{H}\alpha) > -0.15$, below the line defined by Schlickmann (2008), and Hα emission predicted by old stellar populations equal or greater than the observed value ('retired mimicking LINERs').

We have also divided our sample and subsamples into six present-day stellar mass bins centred in $\log M_\star/M_\odot = 10.0$ (A), 10.3 (B), 10.6 (C), 10.9 (D), 11.2 (E) and 11.5 (F), each one 0.30 dex wide. In the same vein as our previous works (Asari et al. 2007; Cid Fernandes et al. 2007), defining bins allows us to alleviate the problem of the mass completeness of the sample. We consider narrow mass bins in order to have very similar galaxies inside each bin. Although the starting sample contained a small proportion of galaxies with masses smaller than $10^{10} \, \text{M}_\odot$, we do not consider them in the current analysis. Indeed, due to the redshift cut we imposed, only the most luminous low-mass objects are present and they are not representative of the bulk of galaxies of their mass range.
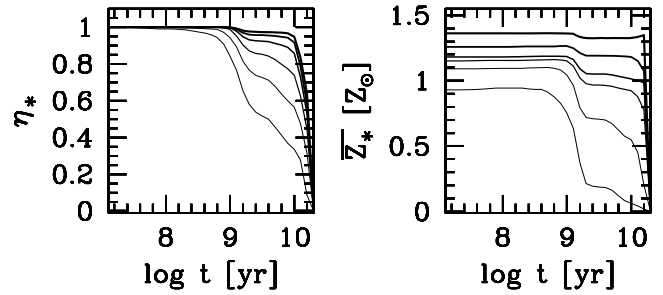
Figure 1. Histories of our parent sample in stellar mass bins. Thicker lines are used for more massive bins. Panels show the median curve for time evolution of stellar mass evolution (left; see equation 1) and metallicity evolution (right).

3 GALAXY HISTORIES IN MASS BINS

As explained in Cid Fernandes et al. (2007), STARLIGHT recovers the fraction x_j that each SSP j contributes to the total light of a galaxy in the spectral range covered by the SDSS. We can translate x_j into the mass fraction *presently locked* into stars, μ_j, or the fraction of mass *ever converted* into stars, μ_j^c.

The stellar mass history can be followed as a function of lookback time t by summing up the converted-mass fractions:

$$\eta_\star(t) = \sum_{t_j > t} \mu_j^c. \tag{1}$$

The mean stellar metallicity at a lookback time t is defined as the total mass in metals locked in stars divided by the total stellar mass at a given time:

$$\overline{Z_\star}(t) = \sum_{t_j > t} \mu_j Z_{\star, j}. \tag{2}$$

Another way to look at the metallicity evolution would be to consider the average metallicity of all the stars born at the same epoch, for each value of t. This, however, is a much less robust quantity, and we found that SSP bases at hand nowadays do not allow such detailed definition.

Fig. 1 shows the median values of $\eta_\star$ and $\overline{Z_\star}$ versus t for mass bins A–F of our sample. As previous studies have already shown (e.g. Cid Fernandes et al. 2007; Panter et al. 2008, for SF galaxies only – here we extend the study for all galaxies), there is a clear *downsizing* effect: the less massive galaxies are slower in converting their mass into stars and in building up their metal content.

4 THE OBSERVED *M–Z* EVOLUTION

Fig. 2 shows the *M–Z* relation. The left-hand panel shows the *present-day M–Z* relation for all the galaxies in our sample. The right-hand panel depicts the *evolution* of the *M–Z* relation for the galaxies in mass bins A–F (black lines): $\overline{Z_\star}(t)$ versus $M_\star(t)$, where $M_\star(t)$ is the stellar mass integrated from the epoch of galaxy formation until a lookback time t, assuming that the stars always pertain to the galaxies where they were born. The resulting *M–Z* relations for different redshifts are plotted in bold lines. One can see that the *M–Z* relation evolves.

As lookback time increases, the *M–Z* relation steepens and covers a larger range of values. As investigated by Panter et al. (2008), using stellar modelling codes other than that of BC03 changes the values of $M_\star(t)$ and $\overline{Z_\star}(t)$, but the general behaviour seen in the present Letter as well as in Panter et al. (2008) remains. One should note that
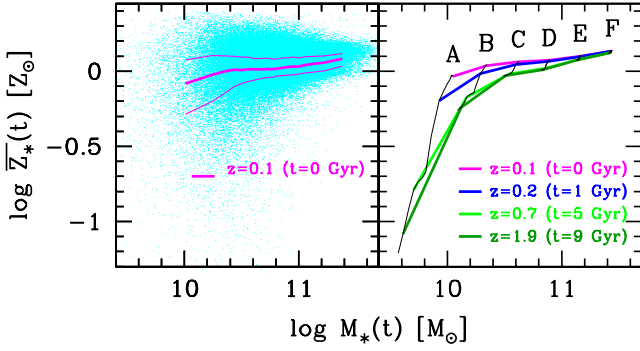
Figure 2. Left: present-day *M–Z* relation for all the galaxies in our sample. The thick line marks the median and thin lines the quartiles. Right: *M–Z* evolution for each of our present-day stellar mass bins A–F (black). From top to bottom, bold lines mark the *M–Z* relation for redshifts $z = 0.1$ ($t = 0$ Gyr), 0.2 (1 Gyr), 0.7 (5 Gyr) and 1.9 (9 Gyr).

the *M–Z* relation and evolution is significantly sample-dependent, which makes difficult any quantitative comparison between works by different authors.

5 A SIMPLE CHEMICAL EVOLUTION MODEL

We now investigate the behaviour of the $M_\star$–$\overline{Z_\star}$ relations shown in Fig. 2 with the help of a simple model of chemical evolution of galaxies. We assume a closed box with initial metallicity equal to zero, and use an instantaneous recycling approximation and a constant yield. The mass-weighted average mass fraction of metals at lookback time t is then given by (Edmunds 1990, equation 35)

$$\overline{Z_\star}(t) = y - y\frac{f(t)\ln(1/f(t))}{(1 - f(t))}, \tag{3}$$

where $f(t)$ is the gas mass fraction and y is the ratio of the mass of metals released per stellar generation to the total stellar mass locked in remnants. The gas mass fraction is given by

$$f(t) = 1 - \left(\frac{1 - R}{M_T}\right)\int_t^{t_o} \mathrm{SFR}(t')\,\mathrm{d}t', \tag{4}$$

where M_T is the total mass of the galaxy (stars and gas), SFR is the star formation rate, R is the returned mass fraction due to stellar winds and supernovae and t_o is the age of the oldest SSP in the base. The star formation rate SFR(t) can be obtained from the results of the STARLIGHT synthesis:

$$\mathrm{SFR}(t)\mathrm{d}t = M_\star^c\mu_\star^c(t), \tag{5}$$

where $M_\star^c$ is the total mass converted into stars ($M_\star^c = M_\star/(1 - R)$). Using equations (1) and (5), $f(t)$ becomes simply

$$f(t) = 1 - (1 - f_{\mathrm{now}})\eta_\star(t), \tag{6}$$

where f_{now} is the present-day gas mass fraction. Knowing the value of y, one can use equations (3) and (6) with $\eta_\star(t)$ given by STARLIGHT to find what value of f_{now} is needed to reproduce the observed evolution of the mean stellar metallicity $\overline{Z_\star}(t)$.

Unfortunately, y is not well known. The measured stellar metallicities are mainly sensitive to the abundance of iron, and the Fe/O ratio is expected to vary with time. For our simple approach, we assume that all the metals vary in lockstep and simply speak of the 'metal yield'. We determine an empirical value of y by applying our model to the highest mass bin of the SF sample, using the Schmidt–

Kennicutt law (Kennicutt 1998)[1] to derive the value of f_{now} from the extinction-corrected Hα luminosity. This procedure should give a reasonable value of the metal yield, since it is for the highest mass bin that the closed-box model is expected to be the most relevant. We obtain $y = 0.03$. This value is in satisfactory agreement with the value (0.04) obtained for a Chabrier (2003) stellar initial mass function by multiplying the oxygen yield from Woosley & Weaver (1995) by the Solar metal-to-oxygen mass fraction.

We therefore adopt $y = 0.03$ and apply our model to try to reproduce the observed metallicity evolution for all the mass bins. Fig. 3 shows $\overline{Z_\star}(t)$ as a function of t for bins A–F of our SF, R and S galaxy samples. The black lines represent the median and quartiles of the observed distributions. The red lines are the model results for the values of f_{now} indicated at the top of each panel. The models were adjusted by eye to reproduce well at least the last 1 Gyr of the observed $\overline{Z_\star}(t)$. For the SF sample, we also indicate the median value of f_{now} obtained from the Schmidt–Kennicutt law. This figure shows that this simple model can reproduce the observed metallicity evolution reasonably well, given the crudeness of our approach. The discrepancies for ages above 10^9 yr are at least partly due to the known problems faced by spectral synthesis in this range (Gomes 2005; Koleva et al. 2008). In particular, the jumps in both $\eta_\star$ and $\overline{Z_\star}$ at ~ 1 Gyr are artefacts related to the spectral libraries used in BC03 (Cid Fernandes et al. 2008). New evolutionary synthesis models with more accurate stellar spectra should improve the recovery of SFHs in this range.

It is worth noting that f_{now} is at least qualitatively in agreement with expectations: it is larger for SF galaxies than for R galaxies, and decreases with increasing $M_\star$. As a matter of fact, for all the mass bins of the SF sample f_{now} is compatible with the values derived from the Schmidt–Kennicutt law (bin E is compatible by construction). S galaxies also show little residual gas mass. The chemical evolution of S galaxies is (within our resolution) similar to the evolution of non-S galaxies.

To sum up, for present-day stellar masses down to 10^{10} M$_\odot$ and within the current limitations of astropaleontology, the closed-box model explains the present-day *M–Z* relation and its evolution quite well if one uses the SFR(t) obtained *directly* from the spectral synthesis of each galaxy. This is not to say that infall or outflow does not play a role. What we want to stress is that it is the SFH which is the main driver of the *M–Z* relation and its evolution.

6 SUMMARY AND DISCUSSION

Until recently, the *M–Z* relation in galaxies had been mostly studied using abundances derived from emission lines. Exploiting the *stellar* metallicities obtained with our spectral synthesis code STARLIGHT, we have obtained the *M–Z* relation at different lookback times for the *same set of galaxies*. The use of stellar metallicities, even if those are not very accurate, has several merits. It allows one to probe metallicities at different epochs of a galaxy evolution. It makes it possible to study galaxies in a larger mass range. Galaxies without emission lines or galaxies with an active nucleus do not have to be discarded. Finally, with stellar metallicities, one avoids the biases that affect the statistical methods used to derive metallicities from emission lines.

---

[1] We use the Schmidt–Kennicutt law for normal disc galaxies (bivariate least-squares regression in fig. 2 of Kennicutt 1998) for a Chabrier (2003) initial mass function, and including the contribution of helium in the gas mass fraction.
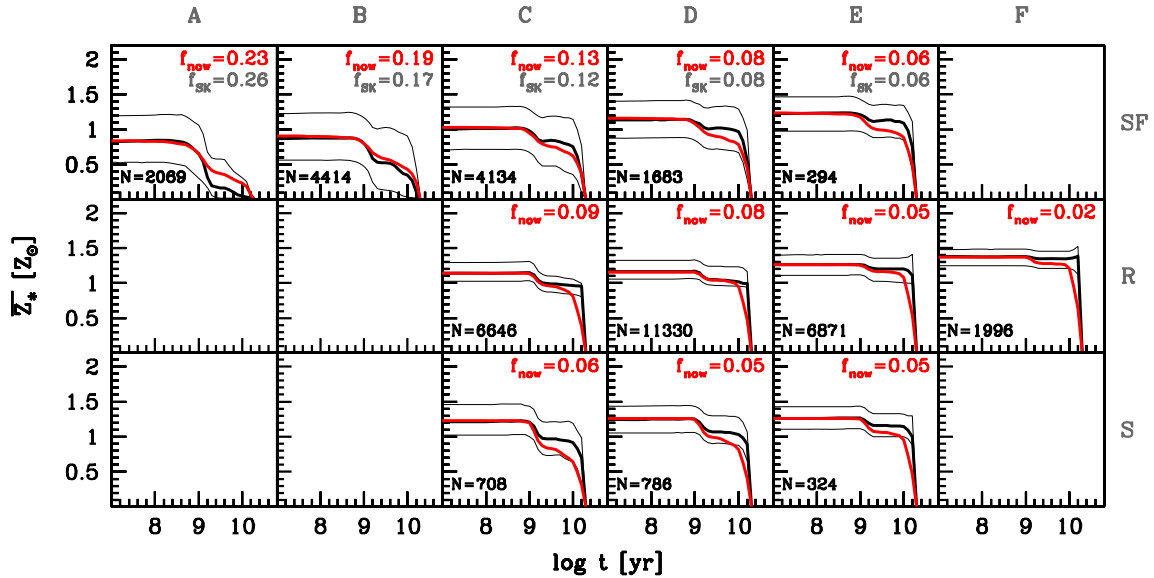
Figure 3. Chemical evolution in our samples of SF, R and S galaxies in the 0.30-dex-wide stellar mass bins, centred in $\log M_\star/M_\odot = 10.0$ (A), 10.3 (B), 10.6 (C), 10.9 (D), 11.2 (E) and 11.5 (F). Each panel shows the median and quartiles of the evolution of $Z_\star$ as found by STARLIGHT (black lines) and as obtained with the simple closed-box model (red lines). The value of f_{now} needed to reproduce the median present-day $Z_\star$ is indicated at the top right of each panel. For the SF sample, we also indicate the median of f_{now} as measured by the Schmidt–Kennicutt law (f_{SK}). The yield y was adjusted to reproduce bin E of the SF sample. The number of galaxies in each panel is indicated at the bottom. Panels were left empty if they contained less than 250 galaxies.

Our main results are the following. We have found that the *M–Z* relation steepens and spans a wider range in both mass and metallicity at higher redshifts. The more massive galaxies show very little evolution since a lookback time of 9 Gyr. This means that they evolved very fast in a distant past, supporting the *downsizing* scenario. This is in agreement with other studies of the build-up of metals in SDSS galaxies as revealed by fossil records, e.g. Cid Fernandes et al. (2007) and Panter et al. (2008).

We have modelled the observed time evolution of the mean stellar metallicity using a closed-box, instantaneous recycling chemical evolution model, for galaxies of different types and masses. We find that this model is compatible with the observations. This suggests that, in the mass range studied here (from $\log M_\star/M_\odot = 9.85$ to 11.65), the *M–Z* relation is mainly driven by the SFH and not by inflows or outflows. By comparing the nebular and stellar metallicities of SDSS galaxies, Gallazzi et al. (2005) had argued that galaxies are not well approximated by closed-box models and that winds may be important. Our study suggests that those processes are not dominant, although they may play a role in the *scatter* of the *M–Z* relation in our mass range.

Low-mass galaxies are not present in our sample because of our selection in redshift. They would require a dedicated study to be compared to the result found by Tremonti et al. (2004) and Garnett (2002) that such galaxies do suffer strong outflows. As a matter of fact, Garnett finds that outflows are important for galaxies with *B*-band magnitude > -18. Only six out of the 82 662 objects in our sample have *g*-band magnitude > -18. Using the Schmidt–Kennicutt law to compute the effective yields for each galaxy (i.e. the yield calculated from the observed nebular metallicities assuming a closed-box model), Tremonti et al. (2004) concluded that galactic winds are ubiquitous and very effective in removing metals from galaxies. This however concerns only galaxies with masses up to $10^{10}\,M_\odot$, which are not present in our sample. Our work emphasizes that there is a large range of galaxy masses – almost two decades – where the closed-box model seems to give a valid representation of the chemical evolution of galaxies.

Our models are parametrized by the present-day gas mass fraction, f_{now}. We have found that the values of f_{now} that allow us to reproduce the observed $\overline{Z_\star}(t)$ histories are larger for less massive galaxies, in agreement with expectations. For galaxies of similar masses, they are larger for SF galaxies than for R galaxies. The values of f_{now} we find for SF galaxies are compatible with those obtained from the Schmidt–Kennicutt law. This sound result supports the validity of our interpretation.

Within our uncertainties, Seyfert galaxies have as little gas as retired galaxies.

ACKNOWLEDGMENTS

REFERENCES

Adelman-McCarthy J. K. et al., 2007, ApJS, 172, 634
Asari N. V., Cid Fernandes R., Stasińska G., Torres-Papaqui J. P., Mateus A., Sodré L., Schoenell W., Gomes J. M., 2007, MNRAS, 381, 263

Baldwin J. A., Phillips M. M., Terlevich R., 1981, PASP, 93, 5

Bruzual G., Charlot S., 2003, MNRAS, 344, 1000 (BC03)

Chabrier G., 2003, PASP, 115, 763

Cid Fernandes R., Mateus A., Sodré L., Stasińska G., Gomes J. M., 2005, MNRAS, 358, 363

Cid Fernandes R., Asari N. V., Sodré L., Stasińska G., Mateus A., Torres-Papaqui J. P., Schoenell W., 2007, MNRAS, 375, L16

Cid Fernandes R. et al., (the SEAGal collaboration), 2008, preprint (arXiv:0802.0849)

Edmunds M. G., 1990, MNRAS, 246, 678

Finlator K., Davé R., 2008, MNRAS, 385, 2181

Gallazzi A., Charlot S., Brinchmann J., White S. D. M., Tremonti C. A., 2005, MNRAS, 362, 41

Garnett D. R., 2002, ApJ, 581, 1019

Gomes J. M., 2005, MSc thesis, Universidade Federal de Santa Catarina

Kennicutt R. C., Jr, 1998, ApJ, 498, 541

Kewley L. J., Ellison S. L., 2008, ApJ, 681, 1183

Koleva M., Prugniel P., Ocvirk P., Le Borgne D., Soubiran C., 2008, MNRAS, 385, 1998

Köppen J., Weidner C., Kroupa P., 2007, MNRAS, 375, 673

Lequeux J., Peimbert M., Rayo J. F., Serrano A., Torres-Peimbert S., 1979, A&A, 80, 155

Maiolino R. et al., 2008, A&A, 488, 463

Mateus A., Sodré L., Cid Fernandes R., Stasińska G., Schoenell W., Gomes J. M., 2006, MNRAS, 370, 721

Panter B., Jimenez R., Heavens A. F., Charlot S., 2008, MNRAS, 391, 1117

Savaglio S. et al., 2005, ApJ, 635, 260

Schlickmann M., 2008, MSc thesis, Univ. Federal de Santa Catarina

Stasińska G., 2008, in Hunt L. K., Madden S., Schneider R., eds, Proc. IAU Symp. 255, Low-Metallicity Star Formation: From the First Stars to Dwarf Galaxies. Cambridge Univ. Press, Cambridge, p. 375

Stasińska G., Cid Fernandes R., Mateus A., Sodré L., Asari N. V., 2006, MNRAS, 371, 972

Stasińska G., Vale Asari N., Cid Fernandes R., Gomes J. M., Schlickmann M., Mateus A., Schoenell W., Sodré L., Jr, 2008, MNRAS, 391, L29

Tremonti C. A. et al., 2004, ApJ, 613, 898

Woosley S. E., Weaver T. A., 1995, ApJS, 101, 181

This paper has been typeset from a TeX/LaTeX file prepared by the author.