The redshift evolution of oxygen and nitrogen abundances in emission-line SDSS galaxies

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ABSTRACT

The oxygen and nitrogen abundance evolutions with redshift and galaxy stellar mass in emission-line galaxies from the Sloan Digital Sky Survey (SDSS) are investigated. This is the first such study for nitrogen abundances, and it provides an additional constraint for the study of the chemical evolution of galaxies. We have devised a criterion to recognize and exclude from consideration active galactic nuclei (AGNs) and star-forming galaxies with large errors in the line flux measurements. To select star-forming galaxies with accurate line fluxes measurements, we require that, for each galaxy, the nitrogen abundances derived with various calibrations based on different emission lines agree. Using this selection criterion, subsamples of star-forming SDSS galaxies have been extracted from catalogs of the MPA/JHU group. We found that the galaxies of highest masses,
those with masses $\gtrsim 10^{11.2}M_\odot$, have not been enriched in both oxygen and nitrogen over the last $\sim 3$ Gyr: they have formed their stars in the so distant past that these have returned their nucleosynthesis products to the interstellar medium before $z=0.25$. The galaxies in the mass range from $\sim 10^{11.0}M_\odot$ to $\sim 10^{11.2}M_\odot$ do not show an appreciable enrichment in oxygen, but do show some enrichment in nitrogen: they also formed their stars before $z=0.25$ but later in comparison to the galaxies of highest masses; these stars have not returned nitrogen to the interstellar medium before $z=0.25$ because they have not had enough time to evolve. This suggests that stars with lifetimes of 2–3 Gyr, in the 1.5–2 $M_\odot$ mass range, contribute to the nitrogen production. Finally, galaxies with masses $\lesssim 10^{11}M_\odot$ show enrichment in both oxygen and nitrogen during the last 3 Gyr: they have undergone appreciable star formation and have converted up to $\sim 20\%$ of their mass into stars over this period. Both oxygen and nitrogen enrichments increase with decreasing galaxy stellar mass in the mass range from $\sim 10^{11}M_\odot$ to $\sim 10^{10}M_\odot$, then slightly decrease with further decrease of galaxy mass.

Subject headings: galaxies: abundances – galaxies: evolution – galaxies: ISM: – H II regions

1. INTRODUCTION

The study of various correlations between the global properties of galaxies is very important for the understanding of their formation and evolution. Among these correlations, the one between galaxy mass and metallicity is one of the most important. Lequeux et al. (1979) first showed that the oxygen abundance correlates well with total mass for a sample of dwarf irregular and blue compact galaxies, in the sense that the higher the total mass, the higher the heavy element content. Since the galaxy mass is a poorly known parameter, the luminosity – metallicity relation has often been considered instead of the mass – metallicity relation. Garnett & Shields (1987) found that abundances of spiral galaxies correlate well with their luminosities. The luminosity – metallicity relation for nearby galaxies has been considered subsequently by many authors (Garnett & Shields 1987; Skillman, Kennicutt & Hodge 1989; Vila-Costas & Edmunds 1992; Richer & McCall 1995; Pilyugin 2001b; Zaritsky, Kennicutt & Huchra 1994; Pilyugin, Vílchez, & Contini 2004; Guseva et al. 2009, among others).

In recent years, the number of available spectra of emission-line galaxies has increased dramatically due to the completion of several large spectral surveys. Measurements of emission lines in those spectra have been carried out for abundance determinations and inves-
tigation of the luminosity–metallicity relation. Thus, Melbourne & Salzer (2002) have considered the luminosity–metallicity relation for 519 galaxies in the KPNO International Spectroscopic Survey (KISS), Lamareille et al. (2004) for 6,387 galaxies in the 2dF Galaxy Survey, Tremonti et al. (2004) for about 53,000 galaxies in the Sloan Digital Sky Survey (SDSS), and Asari et al. (2007) for 82,302 SDSS galaxies.

It has been found, however, that, when mass can be determined, the mass-metallicity correlation is considerably tighter than the luminosity–metallicity correlation, suggesting that mass may be a more meaningful physical parameter than luminosity. In the last decade, the evolution of the mass-metallicity relation with redshift has been examined by many investigators (Lilly, Carollo, & Stockton 2003; Savaglio et al. 2005; Erb et al. 2006; Cowie & Barger 2008; Maiolino et al. 2008; Lamareille et al. 2009; Lara-López et al. 2009). In those investigations, oxygen abundances have been derived using various methods. The general conclusion from those studies is that the oxygen abundance change of star-forming galaxies over the last half of the age of the universe appears to be somewhat moderate, with $\Delta(\log(O/H)) \sim 0.3$ or lower. This change is comparable to or less than the scatter in the observed oxygen abundances (see Fig.10 of Lilly, Carollo, & Stockton (2003), Fig.13 of Savaglio et al. (2005), and Fig.6 of Lara-López et al. (2009)).

Until now, no attention has been paid to the redshift evolution of nitrogen abundances in galaxies, despite the fact that they present several advantages for the study of the chemical evolution of galaxies. First, since at $12 + \log(O/H) \gtrsim 8.3$, secondary nitrogen becomes dominant and the nitrogen abundance increases at a faster rate than the oxygen abundance (Henry, Edmunds & Köppen 2000), then the change in nitrogen abundances with redshift should show a larger amplitude in comparison to oxygen abundances and, as a consequence, should be easier to detect. Furthermore, there is a time delay in the nitrogen production as compared to oxygen production (Maeder 1992; van den Hoek & Groenewegen 1997; Pagel 1997). This provides an additional constraint on the chemical evolution of galaxies. These reasons have led us to consider here not only the redshift evolution of oxygen abundances but also that of nitrogen abundances. To carry out such an investigation, it is necessary to derive accurate oxygen and nitrogen abundances.

The emission line properties of photoionized H\textsc{ii} regions are governed by its heavy element content and by the electron temperature distribution within the photoionized nebula. In turn, the latter is controlled by the ionizing star cluster spectral energy distribution and by the chemical composition of the H\textsc{ii} region. The evolution of a giant extragalactic H\textsc{ii} region associated with a star cluster is thus caused by a gradual change in time of the integrated stellar energy distribution due to stellar evolution. This has been the subject of numerous investigations (Stasińska 1978, 1980; McCall, Rybski & Shields 1985; Dopita & Evans...
The general conclusion from those studies is that HII regions ionized by star clusters form a well-defined fundamental sequence in different emission-line diagnostic diagrams. The existence of such a fundamental sequence forms the basis of various investigations of extragalactic HII regions.

First, Baldwin, Phillips & Terlevich (1981) have suggested that the position of an object in some well-chosen emission-line diagrams can be used to separate HII regions ionized by star clusters from other types of emission-line objects. This idea has found general acceptance and use. Thus, the [OIII]λ5007/Hβ vs [NII]λ6584/Hα diagram has been used widely to distinguish between star-forming galaxies and active galactic nuclei (AGNs). In particular, the SDSS emission-line galaxies occupy a well-defined region shaped like the wings of a seagull (Stasińska et al. 2008). The left wing consists of star-forming galaxies while the right wing is attributed to AGNs. However, the exact location of the dividing line between HII regions and AGNs is still controversial (Kewley et al. 2001; Kauffmann et al. 2003; Stasińska et al. 2006).

Second, Pagel et al. (1979) and Alloin et al. (1979) have suggested that the positions of HII regions in some emission-line diagrams can be calibrated in terms of their oxygen abundances. This approach to abundance determination in HII regions, usually referred to as the “strong line method” has been widely adopted, especially in cases where the temperature-sensitive [OIII]λ4363 line is not detected. Numerous relations have been suggested to convert metallicity-sensitive emission-line ratios into metallicity or temperature estimates (Dopita & Evans 1986; Zaritsky, Kennicutt & Huchra 1994; Pilyugin 2000, 2001a; Pilyugin & Thuan 2005; Pettini & Pagel 2004; Tremonti et al. 2004; Liang et al. 2006; Stasińska 2006, among many others)

It should be noted that the classic T_e method, which relies on the electron temperature T_e determined from the [O III] λ4363 line, is also based on the existence of the fundamental sequence of HII regions. Indeed, when only one electron temperature, t_3 or t_2, is measured (t_3 and t_2 being the electron temperatures in the [O III] and [O II] zones, respectively) it is standard practice to use a t_2 – t_3 relation to estimate the other temperature. This relation is usually established on the basis of HII regions models which belong to the same fundamental sequence.

Our study will be based on the SDSS data base of a million spectra. To study the redshift evolution of oxygen and nitrogen abundances, accurate oxygen and nitrogen abundance determinations are mandatory. The determination of accurate abundances in HII regions from SDSS spectra poses two problems. First, line fluxes in SDSS spectra are measured by an automatic procedure. This inevitably introduces large flux errors for some objects.
We need to devise a way to recognize those objects and exclude them from consideration. Second, the SDSS galaxy spectra span a large range of redshifts. There is thus an aperture-redshift effect in SDSS spectra. Indeed, they are obtained with 3-arcsec-diameter fibers. At a redshift of $z=0.05$ the projected aperture diameter is $\sim 3$ kpc, while it is $\sim 15$ kpc at a redshift of $z=0.25$. This means that, at large redshifts, SDSS spectra are closer to global spectra of whole galaxies, i.e. to that of composite nebulae including multiple star clusters, rather than to spectra of individual H$\text{II}$ regions. One should then expect that some SDSS objects will not follow the fundamental H$\text{II}$ region sequence. These need also to be identified and excluded from our sample.

We propose here a method to recognize objects that suffer from one or both of these problems. It is based on the idea that if i) an object belongs to the fundamental H$\text{II}$ region sequence, and ii) its line fluxes are measured accurately, then the different relations between the line fluxes and the physical characteristic of H$\text{II}$ regions, based on different emission lines, should yield similar physical characteristics (such as electron temperatures and abundances) of that object.

The relations used for the determination of oxygen and nitrogen abundances and for the selection of star-forming galaxies with accurate line flux measurements are derived in Section 2. The selected subsamples of SDSS galaxies are described in Section 3. The relations between redshift, galaxy mass and metallicity are discussed in Section 4. Section 5 presents the conclusions.

Throughout the paper, we will be using the following notations for the line fluxes:

- $R_2 = [\text{O}\text{II}]\lambda3727+\lambda3729 = I_{[\text{OII}]\lambda3727+\lambda3729}/I_{\text{H}\beta}$,
- $N_2 = [\text{N}\text{II}]\lambda6548+\lambda6584 = I_{[\text{NII}]\lambda6548+\lambda6584}/I_{\text{H}\beta}$,
- $R_3 = [\text{O}\text{III}]\lambda4959+\lambda5007 = I_{[\text{OIII}]\lambda4959+\lambda5007}/I_{\text{H}\beta}$,

The electron temperatures will be given in units of $10^4$K, and the stellar masses of galaxies in solar units.

2. METALLICITY AND TEMPERATURE CALIBRATIONS

We noted above that many relations have been proposed to convert various metallicity-sensitive emission-line combinations into metallicity or temperature estimates. The oxygen abundances derived with these different calibrations are not in good agreement, with differences amounting up to 0.7 dex \cite{KewleyEllison2008}. In fact, there appears to exist as many different oxygen abundance scales as there are calibrations. Which metallicity scale is the correct one? There is strong evidence in favour of the metallicity scale defined by
the classic $T_e$ method, considered the most reliable one (see the discussion in Pilyugin 2003; Bresolin et al. 2009b). Indeed, the oxygen abundances derived with the $T_e$ method have been confirmed by high-precision model-independent determinations of the interstellar oxygen abundance in the solar vicinity, using high-resolution observations of the weak interstellar O I λ1356 absorption line towards stars, and by recent determinations of stellar abundances. To put our derived abundances on the $T_e$ scale, we will use H II regions with $T_e$-based abundances as the basis of our calibrations.

To establish the relations between different line fluxes and the physical characteristic of H II regions, we will be using the data for high-metallicity H II regions in nearby galaxies compiled by Pilyugin et al. (2009). We have added to this compilation the recent spectrophotometric measurements of Saviane et al. (2008); Bresolin et al. (2009a,b); Esteban et al. (2009). The oxygen and nitrogen abundances in those H II regions were rederived in an uniform way within the framework of the standard H II region model with a two-zone temperature distribution within the nebula. The equations for the electron temperatures and oxygen ionic abundances were taken from Izotov et al. (2006). The relation between the electron temperature $t_2$ within the O$^+$ zone and $t_3$, that within the O$^{++}$ zone, is

$$t_2 = 0.672t_3 + 0.314.$$  

(1)

This relation derived in Pilyugin et al. (2009) is very close to the commonly used one (Campbell, Terlevich & Melnick 1986; Garnett 1992).

The abundance of the nitrogen ion N$^+$ is derived from the equation

$$\log \frac{N^+}{O^+} = \log \frac{N_2}{R_2} + 0.273 - \frac{0.726}{t_2} - 0.02 \log t_2 + 0.007t_2.$$  

(2)

The total nitrogen abundance is determined from

$$\log \frac{N}{H} = \log \frac{O}{H} + \log \frac{N}{O}$$  

(3)

with the assumption

$$\frac{N^+}{O^+} = \frac{N}{O}.$$  

(4)

It is common practice, in constructing the calibration, to establish relations between the oxygen abundances and the strong-line fluxes. As a result, oxygen abundances are the best studied. In particular, the redshift evolution of oxygen abundances has been the subject of several recent investigations, as noted above. Here, we will adopt a different method. We will calibrate the positions of H II regions in three different diagnostic diagrams in terms of nitrogen abundances, to which less attention has been paid. The oxygen abundance will
then be estimated from the obtained nitrogen abundance and the N/O ratio using equations (2) and (3). The independent determination of nitrogen abundances and of their redshift evolution will provide an independent check of the conclusions derived from the study of the redshift evolution of oxygen abundances.

Fig. 1 shows the nitrogen abundance as a function of log(N$_2$) (upper panel), log(N$_2$/R$_2$) (middle panel), and log(N$_2$/R$_3$) (lower panel). The filled circles are HII regions with measured electron temperatures t$_{3,\text{O}}$ (the auroral line [OIII]λ4363 is available). The open circles are HII regions with measured electron temperatures t$_{2,N}$ (the auroral line [NII]λ5755 is available). Those data have been fitted by the cubic expression

$$12 + \log(N/H) = a_0 + a_1 X + a_2 X^2 + a_3 X^3$$  \hspace{1cm} (5)

where X is successively X=log(N$_2$), X=log(N$_2$/R$_2$), and X=log(N$_2$/R$_3$). The derived curves are shown in Fig. 1 by solid lines. The constant coefficients in Eq. (5) for all three cases are given in Table 1.

Fig. 2 shows the electron temperature t$_2$ as a function of log(N$_2$) (upper panel), log(N$_2$/R$_2$) (middle panel), and log(N$_2$/R$_3$) (lower panel) for the same sample of HII regions. Those data have also been fitted by the cubic expression

$$t_2 = a_0 + a_1 X + a_2 X^2 + a_3 X^3$$  \hspace{1cm} (6)

where X is successively X=log(N$_2$), X=log(N$_2$/R$_2$), and X=log(N$_2$/R$_3$). The derived curves are shown in Fig. 2 by solid lines. The constant coefficients in Eq. (6) for all three cases are also given in Table 1.

The relations between nitrogen abundances and the abundance-sensitive indexes N$_2$, N$_2$/R$_2$, and N$_2$/R$_3$ will be used for the determination of nitrogen abundances in the SDSS galaxies. They will also serve to select star-forming galaxies with accurate line fluxes measurements. As for the relations between the electron temperature t$_2$ and the N$_2$, N$_2$/R$_2$, and N$_2$/R$_3$ indexes, they will be used for estimating the N/O ratios and deriving the O/H oxygen abundances from the N/H nitrogen abundances.

3. SAMPLE SELECTION

Line flux measurements in SDSS spectra have been carried out by several groups. We use here the data in several catalogs made available publicly by the MPA/JHU group. These

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1 The catalogs are available at [http://www.mpa-garching.mpg.de/SDSS/](http://www.mpa-garching.mpg.de/SDSS/)
catalogs give line flux measurements, redshifts and various other derived physical properties such as stellar masses for a large sample of SDSS galaxies. The techniques used to construct the catalogues are described in Brinchmann et al. (2004); Tremonti et al. (2004) and other publications of those authors. We have chosen to use these catalogues instead of the original SDSS spectral database because they contain generally more accurate line flux measurements (see a discussion of the errors in the line flux measurements by Brinchmann et al. (2004)).

In a first step, we extract from the MPA/JHU catalogs all emission-line objects with measured fluxes in the H\(\beta\), H\(\alpha\), [O\(\text{II}\)]\(\lambda\lambda\)3727,3729, [O\(\text{III}\)]\(\lambda\)4959, [O\(\text{III}\)]\(\lambda\)5007, [N\(\text{II}\)]\(\lambda\)6548, [N\(\text{II}\)]\(\lambda\)6584, [S\(\text{II}\)]\(\lambda\)6717, and [S\(\text{II}\)]\(\lambda\)6731 emission lines. The hydrogen, oxygen and nitrogen lines will serve to estimate oxygen and nitrogen abundances relative to hydrogen, and the ratio of the sulfur line intensities is an indicator of electron density. Since our calibrations are only valid in the low-density limit, we have included only those objects with a reasonable value of the [S\(\text{II}\)] ratio, i.e. those with 1.25 < \(F_{[\text{SII}]\lambda6717}/F_{[\text{SII}]\lambda6731}\) < 1.5. This results in a sample containing 118,544 objects which will be referred to hereafter as the total sample. The wavelength range of the SDSS spectra is 3800 – 9300 \(\text{Å}\) so that for nearby galaxies with redshift \(z \lesssim 0.02\), the [O\(\text{II}\)]\(\lambda\lambda\)3727+3729 emission line is out of that range. The absence of this line prevents the determination of the oxygen abundance, so all SDSS galaxies with \(z \lesssim 0.02\) were also excluded. Thus, all galaxies in our total sample have redshifts greater than \(\sim 0.023\), i.e. they are more distant than \(\sim 100\) Mpc. The redshift \(z\) and stellar mass \(M_S\) of each galaxy were also taken from the MPA/JHU catalogs.

The emission-line fluxes are then corrected for interstellar reddening using the theoretical H\(\alpha\) to H\(\beta\) ratio and the analytical approximation to the Whitford interstellar reddening law from Izotov, Thuan & Lipovetsky (1994). In several cases, the derived value of the extinction c(H\(\beta\)) is negative and has been set to zero.

For each galaxy, we have estimated three values of the nitrogen abundance and three values of the electron temperature \(t_2\), using the calibrations discussed above and the dereddened \(N_2\), \(R_2\), \(R_3\) line intensities. Since measurements of the [N\(\text{II}\)]\(\lambda\)6584 line are more reliable than those of the [N\(\text{II}\)]\(\lambda\)6548 line, we have used \(N_2 = 1.33[N\(\text{II}\)]\(\lambda\)6584\) instead of the standard \(N_2 = [N\(\text{II}\)]\(\lambda\)6548 + [N\(\text{II}\)]\(\lambda\)6584\). Then the mean value \(N/H\) of the nitrogen abundance for each galaxy is determined as

\[
\log(N/H)_{\text{mean}} = \frac{\log(N/H)_{N_2} + \log(N/H)_{N_2/R_2} + \log(N/H)_{N_2/R_3}}{3}.
\]

The mean value of the electron temperature \(t_2\) is determined in a similar way. Using \(N/H\) and the mean \(t_2\), the N/O ratio and the oxygen abundance O/H are then derived using equations (2) and (3).

We have suggested above that if the object belongs to the fundamental sequence of HII
regions, and \( ii \) its line fluxes are measured accurately, then the calibrations based on different lines should result in similar abundances. We have calculated for each galaxy the deviations of individual values of the nitrogen abundance from the mean value \( \Delta \log(N/H)_{N_2,N_2/R_2,N_2/R_3} = \log(N/H)_{N_2,N_2/R_2,N_2/R_3} - \log(N/H)_{\text{mean}} \). The mean deviation \( \Delta \log(N/H)_{\text{mean}} \) and the maximum deviation \( \Delta \log(N/H)_{\text{max}} \) were also computed for each object. We have then used the value of \( \Delta \log(N/H)_{\text{max}} \) as a selection criterion to extract from the total sample three subsamples of star-forming galaxies with accurate line flux measurements, going from the most stringent requirement to the least stringent one:

- Subsample A contains only objects with \( \Delta \log(N/H)_{\text{max}} \leq 0.05 \), a total of 15,548 galaxies.
- Subsample B contains only objects with \( \Delta \log(N/H)_{\text{max}} \leq 0.10 \), a total of 55,189 galaxies.
- Subsample C contains only objects with \( \Delta \log(N/H)_{\text{max}} \leq 0.15 \), a total of 84,364 galaxies.

Does selecting objects in such a way give us only \( 1 \) star-forming galaxies and \( 2 \) with accurate line flux measurements? We can test the reliability of our selection criterion concerning the first point by appealing to the \([\text{OIII}]\lambda 5007/\text{H}\beta \) vs \([\text{NII}]\lambda 6584/\text{H}\alpha \) diagram which is often used to distinguish between star-forming galaxies and AGNs. Fig.3 shows such diagrams for subsamples A, B, C and for the total sample. The solid line, taken from \( \text{Kauffmann et al. (2003)} \), shows the dividing line between \( \text{HII} \) regions ionized by star clusters and AGNs. Fig.3 clearly shows that, while the total sample contains both star-forming galaxies and AGNs (lower right panel), our criterion does select out subsamples containing only star-forming galaxies.

Concerning the second point, Fig.4 shows the classical \( R_3 - R_2 \) diagram for subsamples A, B, and C and the total sample. Each galaxy is plotted as a gray (light blue in the electronic version) open circle. For comparison, \( \text{HII} \) regions in nearby galaxies with accurate line flux measurements, from the compilation of \( \text{Pilyugin, Vilchez, & Contini (2004)} \), are shown as black filled circles. Inspection of Fig.4 shows that the selected subsamples of galaxies occupy the same area in the \( R_3 - R_2 \) diagram as the \( \text{HII} \) regions in nearby galaxies with accurate measurements, while the total sample covers a considerably larger area. Evidently, our selection criterion picks out objects which have line intensities that are in agreement with the well-measured line intensities of \( \text{HII} \) regions in nearby galaxies.

We next investigate the \( O/H - N/O \) diagram (Fig.5). As before, the SDSS galaxies from subsamples A, B, and C are shown as gray (light-blue in the electronic version) open circles, and the \( \text{HII} \) regions in nearby galaxies with recent precise measurements of electron temperatures \( \text{[Bresolin 2007; Bresolin et al. 2009a]} \) are shown as black filled circles. We see that the selected SDSS galaxies and the \( \text{HII} \) regions in nearby galaxies with precise measurements lie in the same general region in the \( O/H - N/O \) diagram. However, the selected SDSS galaxies are shifted systematically toward lower N/O ratios. This slight
systematic shift (of \(\sim 0.2\)-0.3 dex in log N/O) can be understood in the following way. The selection criteria pick out galaxies with strong ongoing star formation, resulting in a higher star formation rate in the selected SDSS galaxies as compared to normal galaxies with the same mass. It has long been known that such a star formation burst would cause a temporary decrease of the N/O ratio in the galaxy (e.g. Pilyugin [1992, 1993]).

We now compare the properties of the galaxies in subsamples A, B, and C. The histograms of galaxy stellar masses, redshifts, oxygen and nitrogen abundances for the three subsamples are shown in Fig.6. The locations of the galaxies in the three subsamples in the redshift – galaxy stellar mass diagram are presented in Fig.7. Examination of the distributions of the parameters in the three subsamples reveals that, while they are somewhat similar for subsamples B and C, the distribution for subsample A differs significantly. In particular, there is a shift toward higher masses (by about 0.2 dex) of the galaxy mass distribution in subsample A relative to the other two subsamples. There is also a shift toward higher nitrogen abundances (by about 0.1 dex) of galaxies in subsample A relative to subsamples B and C (see Fig.6). These shifts seem to be caused by a too restrictive selection criterion. The selection condition for subsample A, \(\Delta \log(N/H)_{\text{max}} \leq 0.05\), appears to be too constraining, eliminating too many galaxies and, as a consequence, causing a selection effect. In order not to bias our results, we will consider, in the remainder of the paper, subsample B as the basic subsample, while subsample C will be used as a control subsample.

4. THE REDSHIFT EVOLUTION OF OXYGEN AND NITROGEN ABUNDANCES

We investigate here the changes in oxygen and nitrogen abundances with galaxy stellar mass and redshift. Examination of Fig.6 and Fig.7 shows that such a study is justified only in the range of stellar galaxy masses from \(\sim 10^{9.5}M_\odot\) to \(\sim 10^{11.5}M_\odot\), where the number of galaxies is large enough to give good statistics.

4.1. The \(z-M_S-O/H\) relation

We first discuss the evolution of oxygen abundances with galaxy stellar masses. The upper panel of Fig.8 shows the oxygen abundances of galaxies in subsample B, with redshifts in the range \(0.04 < z < 0.06\), as a function of galaxy stellar mass. The lower panel of Fig.8 shows the same diagram, but for galaxies in a higher redshift range, \(0.23 < z < 0.27\). We note that our \(M_S-O/H\) diagram is very similar to that of Erb et al. (2006) (see their Fig.3). This
may not be surprising since those authors also used a N$_2$ calibration to estimate the oxygen abundances of their SDSS galaxies. Fig. 8 shows that the oxygen abundance increases with increasing galaxy stellar mass up to a value M$_*$. For galaxies with M$_S > M'_S$, the oxygen abundance becomes constant. Comparison of the upper and lower panels of Fig. 8 reveals that the value of M$_*$_S depends on redshift, shifting to higher values at higher redshifts.

To be more quantitative, we approximate the change in oxygen abundance with redshift and galaxy stellar mass by the following “redshift – galaxy stellar mass – oxygen abundance” z–M$_S$–O/H relation:

\[
12 + \log(O/H) = a_1 + a_2 z + (a_3 + a_4 z) \log\left(\frac{M_S}{M'_S}\right), \quad M_S \leq M'_S
\]

\[
12 + \log(O/H) = a_1 + a_2 z, \quad M_S \geq M'_S
\]

\[
\log\left(\frac{M'_S}{M_\odot}\right) = a_5 + a_6 z
\]

Fitting the data for galaxies in subsample B gives the following:

\[
12 + \log(O/H) = 8.67 - 0.027 z + (0.41 - 0.76 z) \log\left(\frac{M_S}{M'_S}\right), \quad M_S \leq M'_S
\]

\[
12 + \log(O/H) = 8.67 - 0.027 z, \quad M_S \geq M'_S
\]

\[
\log\left(\frac{M'_S}{M_\odot}\right) = 9.60 + 5.65 z
\]

The derived z–M$_S$–O/H relation for subsample B is shown in Fig. 8 by the solid line for z=0.05, and by the dashed line for z=0.25.

To test the robustness of the derived z–M$_S$–O/H relation, we have also analyzed subsample C in a similar way. The data for galaxies in subsample C is shown in Fig. 9. Fitting the subsample C data gives the following:

\[
12 + \log(O/H) = 8.67 - 0.020 z + (0.39 - 0.63 z) \log\left(\frac{M_S}{M'_S}\right), \quad M_S \leq M'_S
\]

\[
12 + \log(O/H) = 8.67 - 0.020 z, \quad M_S \geq M'_S
\]

\[
\log\left(\frac{M'_S}{M_\odot}\right) = 9.54 + 5.90 z
\]

The z–M$_S$–O/H relation for subsample C is shown in Fig. 9 by the solid line for z=0.05, and by the dashed line for z=0.25. Comparison between Fig. 8 and Fig. 9 shows that the obtained z–M$_S$–O/H relations for subsamples B and C are very similar, so that our results appear to be robust. The derived relations should approximate well the redshift evolution of oxygen abundances for z \leq 0.25, corresponding to lookback times of up to \sim 3 Gyr. Beyond z = 0.25, the number of galaxies in each subsample becomes very small (see Fig. 7) and the redshift evolution of abundances cannot be studied with enough statistics. To discuss abundance evolution, we will therefore restrict ourselves to objects with z \leq 0.25. At the low-redshift end, to reduce errors from aperture effects and following the recommendations of Kewley, Jansen & Geller (2005), we will limit ourselves to objects with redshifts z > 0.04. Objects with 0.04 < z < 0.06 will be considered as representative of the present-day epoch.
Fig.10 shows the distribution of the deviations of the oxygen abundances from the derived $z-M_S$–$O/H$ relation for both subsamples B and C. It is seen that the scatter of oxygen abundances about the $z-M_S$–$O/H$ relation is slightly larger for galaxies in subsample C than in subsample B. This effect can also be seen by comparing Fig.8 to Fig.9. Nevertheless, it can be said that, for both subsamples of galaxies, the oxygen abundances follow reasonably well the derived $z-M_S$–$O/H$ relation. The mean deviation is small, being $\sim 0.06$ dex. We thus conclude that the derived relations can be used, in principle, to obtain a rough estimate of the metallicities of SDSS galaxies.

4.2. The metallicity plateau and the oxygen enrichment as a function of galaxy stellar mass

One of the most remarkable features of the $M_S$–$O/H$ relation at the current epoch is the metallicity plateau at high galaxy stellar masses. For the sake of definiteness, we will discuss the results for subsample B. The oxygen abundance increases with galaxy stellar mass until $M_S = 10^{10.9} M_{\odot}$, but then remains approximately constant, equal to $12+\log(O/H)=8.67$, in galaxies with $M_S \gtrsim 10^{10.9} M_{\odot}$ (see the upper panel of Fig.8). What is the physical meaning of such a plateau? The observed oxygen abundance in a galaxy is defined by its astration level or gas mass fraction $\mu$, and by the mass exchange between a galaxy and its environment (Searle & Sargent 1972; Pagel 1997). It is believed that galactic winds do not play a significant role in the chemical evolution of large spiral galaxies (Garnett 2002; Tremonti et al. 2004; Dalcanton 2007) and that the rate of gas infall onto the disk decreases exponentially with time (Matteucci & François 1989; Pilyugin & Edmunds 1996a,b; Calura et al. 2009). The present-day location of a system in the $\mu$–$O/H$ diagram is then governed by its evolution in the recent past, and is only weakly dependent of its evolution on long time-scales (Pilyugin & Ferrini 1998). Therefore the observed oxygen abundance in a large spiral galaxy is mainly defined by its gas mass fraction $\mu$. The presence of a metallicity plateau in the $M_S$–$O/H$ diagram at all redshifts implies then that the high-mass SDSS galaxies have very similar gas mass fractions.

The luminosity–central metallicity relation for nearby spiral galaxies also shows a plateau at high luminosities (Pilyugin, Thuan & Vilchez 2007). This plateau was interpreted as evidence that the gas in the centers of the most metal-rich galaxies has been almost completely converted into stars and that the oxygen abundance in the centers of the most luminous metal-rich galaxies has reached its maximum attainable value of $12+\log(O/H) \sim 8.87$. The plateau for oxygen abundances in the SDSS galaxies is at the level of $12+\log(O/H)=8.67$, i.e. 0.2 dex smaller. The simple model of chemical evolution of galaxies predicts that a
decrease of $\mu$ by 0.1 results in an increase of oxygen abundance by $\sim 0.13$ dex, in the range of $\mu$ from $\sim 0.50$ to $\sim 0.05$ (Pilyugin, Thuan & Vilchez [2007]). Then, the difference between the maximum attainable value of the oxygen abundance and the mean oxygen abundance in high-mass SDSS galaxies, $\Delta(\log(O/H)) \sim 0.2$, corresponds to a difference in gas mass fraction $\Delta \mu \sim 0.15$. Since the maximum attainable oxygen value corresponds to complete astration, i.e. $\mu = 0$, the mean $\mu$ in high-mass SDSS galaxies at the present epoch should be $\sim 15\%$, with a probable range of $\mu$ from $\sim 5\%$ to $\sim 25\%$.

Why do our SDSS subsamples not contain galaxies with abundances as high as the maximum attainable value? The reason has to do with the gas content of the SDSS galaxies in our subsamples. As said before, the maximum attainable value of the oxygen abundance corresponds to the limiting case where the gas has been completely converted into stars. The galaxies in our SDSS subsamples are all characterized by strong emission lines in their spectra, meaning that they are undergoing strong starbursts. This requires in turn that they contain an appreciable amount of gas. In other words, because our galaxies are gas-rich, they have not reached the maximum attainable value of the oxygen abundance which requires complete gas exhaustion. If galaxies were not gas-rich, they would have weak emission lines, unlikely to be measured accurately. There exists thus a lower limit on the gas mass fraction for a galaxy to have accurately measured lines and to be included in our subsamples. In that sense, the observed plateau is likely affected by the selection criteria. We note however that, even in the most evolved nearby spiral galaxies, the H$\text{II}$ region oxygen abundances are generally lower than the maximum attainable value. There is furthermore an aperture effect that slightly lowers the metallicities observed for SDSS galaxies. The maximum attainable value oxygen abundance observed in the central part of some nearby galaxies is usually derived by linearly fitting the variations of H$\text{II}$ region abundances with galactocentric distance, and extrapolating to $R=0$. In the distant SDSS galaxies, because one fiber includes many H$\text{II}$ regions that show decreasing metallicities towards larger galactocentric distances, the oxygen abundances are slightly diluted when averaged over a large region.

In the lower panel of Fig.8, we compare the $M_\text{S}$–O/H relation for local ($z \approx 0.05$) galaxies (solid line) with that for distant ($z \approx 0.25$) ones (dashed line). Three features are to be noted. First, it can be seen that, for the galaxies of highest stellar masses, those with masses $\gtrsim 10^{11} M_\odot$, the plateau value of the oxygen abundance does not change in the redshift interval from 0.05 to 0.25. This implies that the galaxies of highest mass in our SDSS subsamples have reached their highest astration level some 3 Gyr ago, and have been somewhat ”lazy” in their evolution afterwards. Second, for lower mass galaxies with stellar masses $\lesssim 10^{11} M_\odot$, it is seen that the value of the oxygen enrichment during the last 3 Gyr increases with decreasing galaxy mass, in the mass interval from $10^{11} M_\odot$ to $10^{9.9} M_\odot$, as shown by the
widening gap between the solid and dashed curves toward lower masses. At $M_S=10^{9.9}M_\odot$, there is a difference $\Delta \log(O/H) \sim 0.25$ between a local galaxy and one at redshift 0.25. For galaxies with $M_S \leq 10^{9.9}M_\odot$, the oxygen enrichment during the last 3 Gyr slightly decreases with decreasing galaxy mass, the slope of the solid line being slightly steeper than that of the dashed line. Third, the value of $M_S^*$, the mass where the oxygen abundance becomes constant with galaxy stellar mass, is redshift-dependent, becoming higher at larger redshifts.

In summary, analysis of the $z$–$M_S$–$O/H$ relation has led to the following main conclusions.

– The galaxies of highest masses, those with $M_S \gtrsim 10^{11}M_\odot$, have reached their highest astriation level in the past and have not had an appreciable oxygen abundance enrichment during the last $\sim 3$ Gyr.

– The mean value of the oxygen enrichment during the last 3 Gyr in galaxies with stellar masses in the range from $10^{10}M_\odot$ to $10^{11}M_\odot$ is $\Delta \log(O/H) \sim 0.11$, with $\Delta \log(O/H) \sim 0.23$ at $10^{10}M_\odot$ and $\Delta \log(O/H) = 0$ at $10^{11}M_\odot$.

The above picture will now be put to the test through the study of the redshift evolution of nitrogen abundances, which we consider next.

### 4.3. The $z$–$M_S$–$N/H$ relation

We proceed in the same way as in our analysis of the oxygen abundances. The upper panel of Fig.11 shows the nitrogen abundances of the local galaxies in subsample B, with redshifts $0.04 < z < 0.06$, as a function of galaxy stellar mass. The lower panel of Fig.11 shows the same diagram, but for more distant galaxies, with redshifts $0.23 < z < 0.27$. Fig.11 shows that the general behavior of nitrogen abundances with redshift and galaxy stellar mass is similar to that of oxygen abundances. The nitrogen abundance increases with increasing galaxy stellar mass up to a value $M_S^*$ of the stellar mass. Then, for galaxies with $M_S > M_S^*$, the nitrogen abundance remains approximatively constant, reaching a plateau. The value of $M_S^*$ is redshift-dependent, becoming higher at larger redshifts.

The change of nitrogen abundance with redshift and galaxy stellar mass can be approximated by a $z$–$M_S$–$N/H$ relation, similar to the one for oxygen abundances. Fitting the data for galaxies in subsample B results in the following relation:

\[
12 + \log(N/H) = 7.89 - 0.110z + (0.99 - 1.40z) \log(\frac{M_S}{M_S^*}), \quad M_S \leq M_S^* \\
12 + \log(N/H) = 7.89 - 0.110z, \quad M_S \geq M_S^* \quad (11)
\]

\[
\log(M_S^*/M_\odot) = 9.97 + 4.92z
\]

The derived relation is shown in Fig.11 by a solid line for $z=0.05$, and by a dashed line for
Again, to test the robustness of the obtained $z$–$M_S$–$N/H$ relation, we have examined subsample C in a similar way. The data for galaxies in subsample C are plotted in Fig.12. Fitting those data gives:

\[
12 + \log(N/H) = 7.88 - 0.027z + (0.85 - 1.14z) \log\left(\frac{M_s}{M_\odot}\right), \quad M_S < M_S^* \\
12 + \log(N/H) = 7.88 - 0.027z, \quad M_S > M_S^* 
\]

The derived $z$–$M_S$–$N/H$ relation is shown in Fig.12 by a solid line for $z=0.05$, and by a dashed line for $z=0.25$. Comparison of Figures 11 and 12 shows that they are very similar and that the derived $z$–$M_S$–$N/H$ relation is robust.

While the general behavior of nitrogen abundances with redshift and galaxy stellar mass is quite similar to that of oxygen abundances (compare Figs.8 and 11), there are significant differences, due to the different production mechanisms of these two elements. The dependence of the nitrogen abundance on galaxy stellar mass for $M_S < M_S^*$ is considerably steeper than that for oxygen abundances. This is caused by the fact that at oxygen abundances higher than about $12 + \log(O/H) = 8.3$, the metallicity-dependent nitrogen production by intermediate-mass stars starts to dominate. Another remarkable difference concerns $M_S^*$, the mass which marks the transition from the linear regime to the plateau regime: at all redshifts, $M_S^*$ is shifted towards higher values in the $M_S$–$N/H$ diagram as compared to in the $M_S$–$O/H$ diagram. Thus, $\log M_S^*$ is equal to 10.2 and 11.2 at $z = 0.05$ and $z = 0.25$ respectively in the $M_S$–$N/H$ diagram, as compared to 9.9 and 11.0 in the $M_S$–$O/H$ diagram.

We now attempt to understand this $M_S^*$ shift. The time delay in nitrogen production relative to oxygen production plays an important role. Examination of Figs.8 and 11 shows that galaxies with masses $\gtrsim 10^{11.2}M_\odot$ are in the plateau regime in both the $M_S$–$O/H$ and in $M_S$–$N/H$ diagrams, at both $z=0.05$ and $z=0.25$. This means that those galaxies have not undergone appreciable enrichment in both oxygen and nitrogen during the last $\sim 3$ Gyr. Evidently, there has not been appreciable star formation in those galaxies over the redshift range from $z=0.25$ to $z=0.05$. Significant star formation in those galaxies has occurred so long ago that stars have returned their nucleosynthesis products to the interstellar medium before the epoch corresponding to $z=0.25$.

Galaxies with masses between $\sim 10^{11.0}M_\odot$ and $\sim 10^{11.2}M_\odot$ do not show an appreciable enrichment in nitrogen over this period. This suggests that there has not been appreciable star formation in those galaxies over the period from $z=0.25$ to $z=0.05$. However, they do contain stars that were formed before $z=0.25$, but later in comparison to the galaxies of highest masses.
The massive oxygen-producing stars die after a few million years, releasing oxygen in the interstellar medium. By contrast, the nitrogen-producing intermediate-mass stars have longer lifetimes, and so they have not returned nitrogen to the interstellar medium before \( z = 0.25 \) because they have not had enough time to evolve. This also suggests that stars that make a contribution to the nitrogen production have lifetimes of a few Gyr.

The galaxies with masses \( \lesssim 10^{11.0} M_\odot \) show enrichment in both oxygen and nitrogen abundances after the period corresponding to \( z = 0.25 \). This means that appreciable star formation has taken place in those galaxies during the last \( \sim 3 \) Gyr. The nitrogen production increases with decreasing galaxy mass from \( 10^{11.2} M_\odot \) to \( \sim 10^{10.2} M_\odot \) where it reaches a value \( \Delta \log(N/H) \sim 0.65 \), then it decreases with further decrease of galaxy mass.

The lower panel of Fig.10 shows the deviations of nitrogen abundances from the derived \( z-M_S-N/H \) relation for galaxies from both subsamples B (solid line) and C (dashed line). Examination of the upper and lower panels of Fig.10 shows that the lower histogram is broader than the upper one, i.e. that the nitrogen abundances show a larger scatter around the \( z-M_S-N/H \) relation as compared to oxygen abundances around the \( z-M_S-O/H \) relation. The mean deviation for nitrogen abundances is \( \Delta(\log(N/H)) \sim 0.15 \) against \( \Delta(\log(O/H)) \sim 0.06 \) for oxygen abundances. However, nitrogen also spans a significantly larger abundance range, from \( 12+\log(N/H) \sim 6.5 \) to \( 12+\log(N/H) \sim 8.0 \), as compared to oxygen which goes only from \( 12+\log(O/H) \sim 8.25 \) to \( 12+\log(O/H) \sim 8.75 \). Taking into account the differences in range, then the relative scatters around the \( z-M_S-N/H \) and \( z-M_S-O/H \) relations are comparable. It should be emphasized that the larger scatter of nitrogen abundances around the \( z-M_S-N/H \) relation in comparison to the scatter of oxygen abundances around the \( z-M_S-O/H \) relation cannot be attributed to larger errors in nitrogen abundance determinations. Indeed, the O/H values are derived from the N/H and N/O values, and any error in the nitrogen abundance determination is propagated into the error in the oxygen abundance determination. Then, if the large scatter of nitrogen abundances around the \( z-M_S-N/H \) is caused by large errors in the nitrogen abundance determinations, then the oxygen abundances would show a similar or larger scatter around the \( z-M_S-O/H \) relation. Just the opposite is observed.

The larger scatter of nitrogen abundances as compared to that of oxygen abundances can be understood in the following way. The oxygen abundance in a galaxy is mainly defined by its astration level. In contrast, the nitrogen abundance is defined not only by the astration level but depends also on the star formation history of the galaxy. As noted above, a star formation burst results in a temporary decrease of the N/O ratio in a galaxy (e.g. Pilyugin 1992, 1993). As a result, galaxies with a given oxygen abundance can have different N/O ratios and nitrogen abundances, depending on their star formation histories.
We now check that expectation with our data. We use subsample C to have the most statistics. Fig. 13 shows the oxygen and nitrogen abundances as a function of redshift for galaxies with masses in the lower range $10^{10.0} M_\odot - 10^{10.3} M_\odot$ (upper left panel) and in the upper range $10^{11.2} M_\odot - 10^{11.5} M_\odot$ (upper right panel). The N/O abundance ratios of those galaxies as a function of redshift are shown in the lower panels. It can be seen that the galaxies in the two different mass ranges show different behaviors with redshift, reflecting the difference in the level of star formation activity in them. That in the lower mass range is high (those galaxies show an appreciable increase of oxygen abundance with decreasing redshift) while that in galaxies in the upper mass range is very low (those galaxies do not show a significant oxygen enrichment with decreasing redshift). Fig. 13 shows that, in spite of the different behaviors of the oxygen abundances with redshift in the two galaxy mass ranges, the scatter in oxygen abundances at a given redshift is comparable in the two cases, the dispersion of the data points in the low mass range being only slightly larger than that in the high mass range. By contrast, the scatter in the N/O ratios and in the nitrogen abundances at a given redshift is considerably higher for galaxies with high star formation activity (those in the low mass range, left upper and lower panels in Fig. 13) than for galaxies with low star formation activity (those in the high mass range, right upper and lower panels in Fig. 13). At $z=0.05$, oxygen abundances in galaxies with masses $10^{10.0} M_\odot - 10^{10.3} M_\odot$ are similar to those in galaxies with masses $10^{11.2} M_\odot - 10^{11.5} M_\odot$. The maximum value of the N/O ratio in the two galaxy mass ranges is also similar. However, many galaxies in the low mass range possess low N/O ratios (Fig. 13 lower left panel). The fact that the N/O ratios of many galaxies with high star formation activity are significantly lower than those in galaxies with low star formation activity does confirm our expectation that the larger scatter of nitrogen abundances around the $z-M_S-N/H$ in comparison to that of oxygen abundances around the $z-M_S-O/H$ is caused by the temporary decrease of the N/O ratio, due to star formation bursts of different amplitudes and/or ages, i.e. to different star formation histories in galaxies.

Thus, the consideration of the nitrogen abundance evolution with redshift and galaxy stellar mass has confirmed the general picture obtained from the oxygen abundance evolution analysis. Examination of both the $z-M_S-N/H$ and the $z-M_S-O/H$ relations has led to the following conclusions:

- The galaxies of highest masses, those with masses $\gtrsim 10^{11.2} M_\odot$, have reached their high astration level more than 3 Gyr ago, so that stars in those galaxies have returned their nucleosynthesis products to the interstellar medium before $z=0.25$.
- The galaxies with masses in the range from $\sim 10^{11.0} M_\odot$ to $\sim 10^{11.2} M_\odot$ also form their stars before $z=0.25$, but later in comparison to the galaxies of highest masses. The intermediate-mass stars in those galaxies have not returned nitrogen to the interstellar medium before
\( z = 0.25 \) because they have not had enough time to evolve.

– Significant star formation has occurred in galaxies with masses lower than \( \sim 10^{11} M_\odot \) during the last 3 Gyr. Those galaxies have converted up to 20\% of their total mass into stars over this period.

– Stars with lifetimes of a few Gyr contribute to the nitrogen production.

### 4.4. Influence of the selection criteria on the redshift – galaxy mass – metallicity relations

We wish to examine here how our selection criteria affect the results obtained. We compare the results obtained for our SDSS subsamples with those obtained for a sample of star-forming SDSS galaxies selected with commonly used criteria. We use the diagnostic diagram proposed by Baldwin, Phillips & Terlevich (1981) where the excitation properties of H\( \text{II} \) regions are studied by plotting the low-excitation \([\text{N} \text{II}]\lambda 6584/\text{H}\alpha \) line ratio against the high-excitation \([\text{O} \text{III}]\lambda 5007/\text{H}\beta \) line ratio. The diagram can be used to separate different types of emission-line objects according to their main excitation mechanism. We have thus excluded from the total SDSS sample all objects above the solid line given by the equation

\[
\log ([\text{O} \text{III}]\lambda 5007/\text{H}\beta ) = 0.61 \log ([\text{N} \text{II}]\lambda 6584/\text{H}\alpha ) - 0.05 + 1.3
\]  

(13)

which separates objects with H\( \text{II} \) spectra from those containing an AGN (Kauffmann et al. 2003). We have extracted from the total sample a subsample of 95,046 star-forming galaxies, referred to hereafter as the "all star-forming galaxies" or SFG subsample.

We compare the \( z-M_\text{S} - \text{O/H} \) and \( z-M_\text{S} - \text{N/H} \) diagrams for the SFG and C subsamples. The upper panel of Fig.14 shows the oxygen abundances of galaxies in the SFG subsample, with redshifts in the range \( 0.04 < z < 0.06 \), as a function of galaxy stellar mass. The lower panel of Fig.14 shows the same diagram, but for galaxies in a higher redshift range, \( 0.23 < z < 0.27 \). The derived \( z-M_\text{S} - \text{O/H} \) relations for subsample C, superimposed on the data points of the SFG subsample, are shown in Fig.14 by the solid line for \( z = 0.05 \), and by the dashed line for \( z = 0.25 \). Inspection of Fig.14 shows that the galaxies from the SFG subsample follow well the \( z-M_\text{S} - \text{O/H} \) relation derived for subsample C. Comparison of Fig.14 with Fig.9 shows however that the scatter of the points about the \( z-M_\text{S} - \text{O/H} \) relation is larger for the SFG subsample than for subsample C. This is evidence that our selection criteria effectively weeds out galaxies with less reliable measurements.

Fig.15 shows the \( z-M_\text{S} - \text{N/H} \) diagram. As before, the \( z-M_\text{S} - \text{N/H} \) relations derived for subsample C are superimposed on the datapoints of the SFG subsample. Again, the galaxies from the SFG subsample follow well the \( z-M_\text{S} - \text{N/H} \) relation derived for subsample C.
Thus, the results obtained with the commonly used method of selecting star-forming galaxies do not differ appreciably from those obtained with our selection method. We emphasize that our approach presents however two important advantages. First, it is not necessary to know a priori the precise location of the dividing line between \( \text{H} \text{II} \) regions and AGNs, a subject which is, as noted before, still controversial (Kewley et al. 2001; Kauffmann et al. 2003; Stasińska et al. 2006). Second, our approach allows to reject all unreliable measurements. The counterpart of these advantages is that our approach requires a good sample of calibration datapoints – a reasonably large sample of \( \text{H} \text{II} \) regions with precise spectrophotometric measurements, including weak auroral lines – to establish reliable relations between the strong line fluxes and the physical characteristics of \( \text{H} \text{II} \) regions. Those relations should however be established in any case, as they are necessary for abundance determinations in star-forming galaxies, independently of the particular method used to select them.

4.5. Comparison to previous work on the \( z-M_\text{S}-\text{O/H} \) relation

The evolution of the mass-metallicity relation of galaxies with redshift has been considered previously by several groups, as described in the introduction. But, as discussed before, each group uses a different calibration to derive abundances which show as a result sometimes large discrepancies. So it is difficult to directly compare, or put on the same scale, the abundances derived by other groups and our own. Thus, we will not attempt such a comparison. Rather, we will limit ourselves to comparing the evolution in oxygen abundances with redshift which seems to be less sensitive to the adopted calibration. As for the nitrogen evolution with redshift, it has not been considered before.

We first summarize the results obtained by previous investigators. Lilly, Carollo, & Stockton (2003) have estimated the oxygen abundance in a sample of 66 Canada–France Redshift Survey galaxies in the redshift range \( 0.47 < z < 0.92 \), using the flux ratios of bright oxygen emission lines. They concluded that, at half the present age of the universe, the overall oxygen abundance of the galaxies in their sample, with luminosities ranging from \( M_B=–20 \) to \( M_B=–22 \) (or \( \log(L_B/L_{B\odot}) \sim 10.2 – 11.0 \)), is only slightly lower than the oxygen abundance in similar luminous galaxies today. They found a variation \( \Delta(\log(O/H)) = 0.08 \pm 0.06 \).

Savaglio et al. (2005) have investigated the mass-metallicity relation using galaxies from the Gemini Deep Deep Survey and the Canada–France Redshift Survey in the redshift range \( 0.4 < z < 1.0 \). Their galaxies with \( M_\text{S} > 10^{10} M_\odot \) have oxygen abundances close to those in local galaxies of comparable mass, while the oxygen abundances in galaxies with \( M_\text{S} < 10^{10} M_\odot \) are lower on average (with a large scatter) than those in galaxies of similar masses at the present epoch (see their Fig.13).
Cowie & Barger (2008) have studied the oxygen abundance evolution from $z = 0.9$ to $z = 0.05$ using a large sample of galaxies in the Great Observatories Origins Deep Survey–North (GOODS–N). They have found an evolution of the metallicity–mass relation corresponding to a decrease of $0.21\pm0.03$ dex between the value at $z = 0.77$ and the local value in the $10^{10}$–$10^{11} M_\odot$ range. They also found that star formation in the most massive galaxies ($>10^{11} M_\odot$) ceases at $z<1.5$ because of gas starvation.

Lamareille et al. (2009) have derived the mass–metallicity relation of star-forming galaxies up to $z \sim 0.9$ using data from the VIMOS VLT Deep Survey. They found that the galaxies of $10^{10.2}$ solar masses show a larger oxygen enrichment ($\Delta(\log(O/H)) \sim 0.28$) from $z \sim 0.77$ to $z=0$ than the galaxies of $10^{9.4}$ solar masses ($\Delta(\log(O/H)) \sim 0.18$).

Lara-López et al. (2009) have studied the oxygen abundance of relatively massive ($\log(M_\text{S}/M_\odot) \geq 10.5$) star-forming galaxies from SDSS/DR5 at different redshift intervals from 0.4 to 0.04. They found an oxygen enrichment $\Delta(\log(O/H)) \sim 0.1$ from redshift 0.4 to 0.

Asari et al. (2009) have derived the mass–metallicity relation at different lookback times for SDSS galaxies using the stellar metallicities estimated with their spectral synthesis code. They have found that the more massive galaxies show very little evolution since a lookback time of 9 Gyr.

Examination of all these studies shows good qualitative agreement between them, but with a rather large scatter in the estimated values of the oxygen enrichment. The results of these investigations can be summarized as followed: 1) the most massive galaxies (those with masses $>10^{11} M_\odot$) do not show an appreciable enrichment in oxygen from $z \sim 0.7$ to $z = 0$; 2) in the $10^{10}$–$10^{11} M_\odot$ mass range, an increase of the oxygen abundance $\Delta(\log(O/H)) \sim 0.08$–$0.28$ is observed in the redshift range from $z \sim 0.7$ to $z \sim 0$. Our results are also in good qualitative agreement with those previous results. We also see no change in oxygen abundance with redshift for galaxies with masses greater than $10^{11} M_\odot$, in the redshift range from $\sim0.25$ to 0. We estimate the mean increase of the oxygen abundance with redshift in the $10^{10}$–$10^{11} M_\odot$ galaxy stellar mass range to be $\Delta(\log(O/H)) \sim 0.11$, with $\Delta(\log(O/H)) \sim 0.23$ at $10^{10} M_\odot$ and $\Delta(\log(O/H)) = 0$ at $10^{11} M_\odot$. This is in agreement with the upper range of values found in previous works, especially when we take into account the fact that we have considered a smaller redshift interval than previous investigators.
4.6. Nitrogen enrichment by intermediate mass stars: a discrepancy with current stellar evolution theory

Edmunds & Pagel (1978) have suggested that observations of the N/O abundance ratio in galaxies can be understood if N is manufactured in stars of 1–2.5 $M_\odot$. The N/O ratio of a galaxy then becomes an indicator of the time that has elapsed since the bulk of star formation occurred, or in other words of the nominal “age” of the galaxy. Pilyugin, Thuan & Vílchez (2003) have found that the N/O ratios in H II regions of galaxies of early morphological types are systematically higher than those in H II regions of galaxies of late morphological types. Moreover, it is known that the star formation histories of galaxies of different morphological types differ, in the sense that the spiral galaxies of early morphological types have a significantly larger fraction of old stars than the galaxies of late morphological type (Sandage 1986). These two facts lead to the conclusion that the contribution to the nitrogen production by low- and intermediate-mass stars, with a long time delay of a few Gyr between their moment of birth and the time of release of their nucleosynthetic products in the interstellar medium, can be significant.

One of the main conclusions of this study is that there has been a significant evolution in nitrogen abundances in star-forming galaxies over the last 2–3 Gyr. This appears not to agree with the predictions of current theoretical models of intermediate mass stars. Indeed, a time duration of 2–3 Gyr corresponds to the lifetime of stars in the 1.5 – 2 $M_\odot$ mass range. While stellar evolution models of intermediate mass stars have long predicted that they contribute significantly to nitrogen enrichment, it is stars of 3 – 8 $M_\odot$ that are supposed to do the job, not stars in the 1.5 – 2 $M_\odot$ mass range. Intriguingly, there are other types of observations that also suggest that stars in the 1.5 – 2 $M_\odot$ mass range contribute to nitrogen enrichment. Richer & McCall (2008) have found that planetary nebulae in nearby galaxies (with or without ongoing star formation) often show large nitrogen enrichments. They have argued that these planetary nebulae are the descendants of relatively low mass progenitors, of approximately 1.5$M_\odot$ or less, i.e. that low- and intermediate-mass stars are a more important source of nitrogen than has been hitherto considered. Thus, our conclusion that stars with lifetimes of a few Gyr contribute to the nitrogen production, derived from the consideration of the nitrogen abundance evolution with redshift in galaxies, is in line with the conclusions of other types of investigations. While stellar evolution theory does not yet predict nitrogen production in stars with masses of $\sim$ 1.5 – 2 $M_\odot$, several lines of observations now do so.
5. CONCLUSIONS

The redshift evolution of oxygen and nitrogen abundances in emission-line SDSS galaxies has been studied.

We have paid particular attention to the construction of our galaxy sample, using the MPA/JHU catalogs of line flux measurements and other derived physical properties for SDSS galaxies. We have devised a way to recognize and exclude from consideration not only AGNs, but also star-forming galaxies with large errors in their line flux measurements. We have found that the requirement that nitrogen abundances, derived with different calibration relations based on different emission lines, agree, can be used as a reliable criterion to select star-forming galaxies with accurate line fluxes measurements.

We have derived relations between nitrogen abundances and the abundance-sensitive N$_2$, N$_2$/R$_2$, and N$_2$/R$_3$ indexes. Those relations have been used to determine nitrogen abundances in the SDSS galaxies. The small dispersion among the various derived nitrogen abundances for a given galaxy is used as a criterion to select star-forming galaxies with accurate line fluxes measurements. The relations between the electron temperature t$_2$ and the N$_2$, N$_2$/R$_2$, and N$_2$/R$_3$ indexes have also been established. Those calibrations have been used to estimate the N/O ratio and derive the oxygen abundances O/H from the nitrogen abundances N/H.

Subsamples of star-forming SDSS galaxies have been extracted from the MPA/JHU catalogs, using the small nitrogen abundance dispersion criterion described above. The nitrogen and oxygen abundances are estimated for these galaxies. The evolution of the oxygen and nitrogen abundances with redshift and galaxy stellar mass of galaxy are investigated, that of nitrogen abundances for the first time. We have obtained the following main results.

1) The galaxies of highest masses (those more massive than $\sim 10^{11.2}$M$_\odot$) do not show an appreciable enrichment in both oxygen and nitrogen from z=0.25 to z=0.05. Those galaxies have reached their high astration level in such a distant past that their stars have returned their nucleosynthesis products to the interstellar medium before z=0.25.

2) The galaxies in the mass range from $\sim 10^{11.0}$M$_\odot$ to $\sim 10^{11.2}$M$_\odot$ do not show an oxygen enrichment, but do show some enrichment in nitrogen. Those galaxies also formed stars before z=0.25, but at a later epoch in comparison to the galaxies of highest masses. Their stars have not returned nitrogen to the interstellar medium before z=0.25 because they have not had enough time to evolve.

3) The galaxies with masses lower than $\sim 10^{11}$M$_\odot$ show enrichment in both oxygen and nitrogen abundances over the redshift period from z=0.25 to z=0.05, i.e. during the last 3 Gyr. The oxygen enrichment increases with decreasing galaxy mass, from $10^{11}$M$_\odot$ to $M_S=10^{9.9}$M$_\odot$. It reaches a value $\Delta$log(O/H) $\sim 0.25$ at $M_S=10^{9.9}$M$_\odot$ and slightly decreases
with further decrease of galaxy mass. The nitrogen enrichment increases with decreasing galaxy mass, from $\sim 10^{11} M_\odot$ to $\sim 10^{10.2} M_\odot$. It reaches a value $\Delta \log(N/H) \sim 0.65$ at $\sim 10^{10.2} M_\odot$ and slightly decreases with further decrease of galaxy mass. Significant star formation has occurred in those galaxies during the last 3 Gyr. They have converted up to 20% of their total mass to stars over this period.

4) Stars with lifetimes of 2–3 Gyr, i.e. in the 1.5 – 2 $M_\odot$ mass range, contribute to the nitrogen production. This is not in agreement with current stellar evolutionary models of intermediate mass stars which predict that stars in the 3 – 8 $M_\odot$ mass range do the job, not stars in the 1.5 – 2 $M_\odot$ mass range.

5) The general picture of the oxygen abundance evolution with redshift and galaxy stellar mass obtained here and in previous work is confirmed and strengthened by consideration of the nitrogen abundance evolution.

Acknowledgments

We are grateful to the referee for his/her constructive comments. L.S.P. thanks the hospitality of the Astronomy Department of the University of Virginia where part of this investigation was carried out. L.S.P. and I.A.Z. acknowledge the partial support of the Cosmophysical-2 project of the National Academy of Sciences of Ukraine. The authors acknowledge the work of the SDSS team. Funding for the SDSS has been provided by the Alfred P. Sloan Foundation, the Participating Institutions, the National Aeronautics and Space Administration, the National Science Foundation, the U.S. Department of Energy, the Japanese Monbukagakusho, and the Max Planck Society. The SDSS Web site is [http://www.sdss.org/](http://www.sdss.org/) The SDSS is managed by the Astrophysical Research Consortium (ARC) for the Participating Institutions. The Participating Institutions are The University of Chicago, Fermilab, the Institute for Advanced Study, the Japan Participation Group, The Johns Hopkins University, the Korean Scientist Group, Los Alamos National Laboratory, the Max-Planck-Institute for Astronomy (MPIA), the Max-Planck-Institute for Astrophysics (MPA), New Mexico State University, University of Pittsburgh, University of Portsmouth, Princeton University, the United States Naval Observatory, and the University of Washington.

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Table 1. Values of coefficients in Eq. (5) for $12 + \log(N/H)$, and in Eq. (6) for $t_2$

| Y value      | X value      | $a_0$ | $a_1$ | $a_2$ | $a_3$ |
|--------------|--------------|-------|-------|-------|-------|
| $12 + \log(N/H)$ | $\log(N_2)$ | 7.649 | 1.454 | 0.257 | -0.148|
| $12 + \log(N/H)$ | $\log(N_2/R_2)$ | 7.918 | 0.877 | -0.058 | 0.038 |
| $12 + \log(N/H)$ | $\log(N_2/R_3)$ | 7.526 | 0.521 | 0.062 | 0.014 |
| $t_2$         | $\log(N_2)$ | 0.778 | -0.354 | 0.001 | 0.044 |
| $t_2$         | $\log(N_2/R_2)$ | 0.702 | -0.248 | 0.042 | 0.019 |
| $t_2$         | $\log(N_2/R_3)$ | 0.802 | -0.172 | 0.003 | 0.011 |
Fig. 1.— Nitrogen abundance as a function of different abundance-sensitive indexes for H II regions in nearby galaxies with measured electron temperatures $t_{3,O}$ or $t_{2,N}$. The filled circles show H II regions with measured $t_{3,O}$ temperatures. The open circles show H II regions with measured $t_{2,N}$ temperatures. The solid lines are the adopted cubic fits.
Fig. 2.— Electron temperature $t_2$ as a function of different abundance-sensitive indexes for H II regions in nearby galaxies with measured electron temperatures $t_{3,O}$ or $t_{2,N}$. The filled circles show H II regions with measured $t_{3,O}$ temperatures. The open circles show H II regions with measured $t_{2,N}$ temperatures. The solid lines are the adopted cubic fits.
Fig. 3.— The [OIII]λ5007)/Hβ vs [NII]λ6584)/Hα diagram for subsamples A, B, and C and the total sample. The solid line shows the dividing line between HII regions ionized by star clusters and AGNs (Kauffmann et al. 2003).
Fig. 4.— The $R_3 - R_2$ diagram for subsamples A, B, and C and the total sample. The SDSS objects are shown by gray (light-blue in the electronic version) circles. The H\textsc{ii} regions in nearby galaxies from the compilation of Pilyugin, Vílchez, & Contini (2004) are shown by black triangles.
Fig. 5.— The O/H - N/O diagram for subsamples A, B, and C. The SDSS objects are shown by gray (light-blue in the electronic version) open circles. The H II regions in nearby galaxies with measured electron temperatures (Bresolin 2007; Bresolin et al. 2009b) are shown by black filled circles.
Fig. 6.— Normalized histograms of observed and derived properties for SDSS galaxies in subsamples A (short-dashed line), B (solid line), and C (long-dashed line).
Fig. 7.— The redshift – galaxy stellar mass diagram for subsamples A, B, and C.
Fig. 8.— The oxygen abundance – galaxy stellar mass diagrams for subsample B at $z=0.05$ (upper panel) and $z=0.25$ (lower panel). The Z-M$_S$-O/H relation (Eq.9) is shown by the solid line for $z=0.05$ and by the dashed line for $z=0.25$. 
Fig. 9.— The oxygen abundance – galaxy stellar mass diagrams for subsample C at $z=0.05$ (upper panel) and $z=0.25$ (lower panel). The $Z$-$M_S$-O/H relation (Eq.10) is shown by the solid line for $z=0.05$ and by the dashed line for $z=0.25$. 
Fig. 10.— Normalized histograms of oxygen abundance deviations from the Z–M$_S$–O/H relation (upper panel) and nitrogen abundances deviations from the Z–M$_S$–N/H relation (lower panel). In both panels, subsample B is shown by the solid line and subsample C by the dashed line.
Fig. 11.— The nitrogen abundance – galaxy stellar mass diagrams for subsample B at \(z=0.05\) (upper panel) and \(z=0.25\) (lower panel). The Z-M\(S\)-N/H relation (Eq.\textsuperscript{11}) is shown by the solid line for \(z=0.05\) and by the dashed line for \(z=0.25\).
Fig. 12.— The nitrogen abundance – galaxy stellar mass diagrams for subsample C at $z=0.05$ (upper panel) and $z=0.25$ (lower panel). The $Z-M_{\text{S}}$-$N/H$ relation (Eq. 12), is shown by the solid line for $z=0.05$ and by the dashed line for $z=0.25.$
Fig. 13.— The oxygen and nitrogen abundances as a function of redshift for galaxies with masses $10^{10.0}M_\odot-10^{10.3}M_\odot$ (upper left panel) and $10^{11.2}M_\odot-10^{11.5}M_\odot$ (upper right panel). Oxygen abundances are shown by dark (black in the electronic version) filled circles, and nitrogen abundances by gray (light-blue in the electronic version) filled circles. The nitrogen-to-oxygen abundance ratios as a function of redshift for those galaxies are shown in the corresponding lower panels.
Fig. 14.— The oxygen abundance – galaxy stellar mass diagrams for the ”all star-forming galaxies” (SFG) subsample at $z=0.05$ (upper panel) and $z=0.25$ (lower panel). The $z$-$M_S$-O/H relation derived for subsample C (Eq.10) is shown by the solid line for $z=0.05$, and by the dashed line for $z=0.25$. 
Fig. 15.— The nitrogen abundance – galaxy stellar mass diagrams for the "all star-forming galaxies" (SFG) subsample at $z=0.05$ (upper panel) and $z=0.25$ (lower panel). The $z$-$M_S$-$N/H$ relation derived for subsample C (Eq.12), is shown by the solid line for $z=0.05$, and by the dashed line for $z=0.25$. 