THE STAR FORMATION HISTORY AND CHEMICAL EVOLUTION OF
STAR-FORMING GALAXIES IN THE NEARBY UNIVERSE

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ABSTRACT

We have determined the metallicity (O/H) and nitrogen abundance (N/O) of a sample of 122,751 star-forming galaxies (SFGs) from the Data Release 7 of the Sloan Digital Sky Survey. For all these galaxies we have also determined their morphology and obtained a comprehensive picture of their star formation history (SFH) using the spectral synthesis code STARLIGHT. The comparison of the chemical abundance with the SFH allows us to describe the chemical evolution of the SFGs in the nearby universe (z ⩽ 0.25) in a manner consistent with the formation of their stellar populations and morphologies. A high fraction (45%) of the SFGs in our sample show an excess abundance of nitrogen relative to their metallicity. We also find this excess to be accompanied by a deficiency of oxygen, which suggests that this could be the result of effective starburst winds. However, we find no difference in the mode of star formation of the nitrogen-rich and nitrogen-poor SFGs. Our analysis suggests that they all form their stars through a succession of bursts of star formation extended over a period of few Gyr. What produces the chemical differences between these galaxies seems therefore to be the intensity of the bursts: the galaxies with an excess of nitrogen are those that are presently experiencing more intense bursts or have experienced more intense bursts in their past. We also find evidence relating the chemical evolution process to the formation of the galaxies: the galaxies with an excess of nitrogen are more massive, and have more massive bulges and earlier morphologies than those showing no excess. Contrary to expectation, we find no evidence that the starburst wind efficiency decreases with the mass of the galaxies. As a possible explanation we propose that the loss of metals consistent with starburst winds took place during the formation of the galaxies, when their potential wells were still building up, and consequently were weaker than today, making starburst winds more efficient and independent of the final mass of the galaxies. In good agreement with this interpretation, we also find evidence consistent with downsizing, according to which the more massive SFGs formed before the less massive ones.

Key words: galaxies: abundances – galaxies: active – galaxies: evolution – galaxies: stellar content

1. INTRODUCTION

One of the most important achievements of modern astronomy is the discovery of the process of nucleosynthesis of chemical elements in stars. Once properly understood, this process, coupled with the concept of stellar evolution regulated by the different masses of stars, gives us a unique insight about the chemical evolution of galaxies (Edmunds & Pagel 1978; Brodie & Huchra 1991; Zaritsky et al. 1994; Coziol et al. 1998, 1999; Henry et al. 2000; Pilyugin et al. 2003; Pilyugin & Thuan 2011; Torres-Papaqui et al. 2011). For instance, it is now well accepted that oxygen and sulfur are two elements produced by massive stars ($M \geq 8 M_\odot$), while nitrogen is mostly a product of lower mass stars (Renzini & Voli 1981; McCall et al. 1985; Evans & Dopita 1985; Garnett 1990). Consequently, due to the longer time passed on the main sequence by stars with decreasing masses, we would expect some time delay between the enrichment of oxygen and that of nitrogen in galaxies having different ages (Matteucci & Tosi 1985; Garnett 1990; Mollá et al. 2006; Richer & McCall 2008). Assuming that the initial mass function (IMF) does not vary between spiral galaxies, such time delay, when properly documented, may thus reveal something fundamental about how these systems formed their stars; for example, allowing us to distinguish between constant star formation over the formation by a sequence of stellar bursts (Lehnert & Heckman 1996; Coziol et al. 1999; Tremonti et al. 2004).

To determine the “normal” or standard chemical evolution of star-forming galaxies (SFGs) in the nearby universe (z ⩽ 0.25), the observation and study of a large, homogeneous, and statistically representative sample is required. This is where the Sloan Digital Sky Survey (SDSS) project becomes so valuable (York et al. 2000; Hogg et al. 2001; Pier et al. 2003). By applying different automatic algorithms to the enormous data bank produced by the SDSS it is now possible to retrieve one of the largest and homogenous sets of spectral line ratios necessary to estimate the basic chemical abundances, and to describe the chemical evolution process of SFGs in a manner consistent with their star formation histories and morphologies.

In recent articles (Tremonti et al. 2004; Nagao et al. 2006; Izotov et al. 2006; Yin et al. 2007), data from SDSS were already used to verify the consistency of the different methods devised in the past to determine the abundance of elements. One of the difficulties encountered in these studies is related to the rarity of the [O iii] λ4363 line. Theoretically, this line was recognized as crucial in order to determine an accurate temperature for the gas in H II regions. Unfortunately, [O iii] λ4363 can only be observed in very low metallicity SFGs, which form a minute fraction of the SDSS galaxies. This fact emphasizes the importance of developing different empirical methods like $R_{23}$ or $R_3$ to obtain chemical information for a significantly larger sample of galaxies (Pagel et al. 1979; McCall 1984; Vacca & Conti 1992; Thurston et al. 1996; Thuan et al. 2010).

Recently, some authors (e.g., Nagao et al. 2006; Yin et al. 2007) advocated that we need to modify some of the empirical methods applied in previous abundance studies using only galaxies where [O iii] λ4363 was observed. These authors based their claims on the fact that they found apparent significant differences in the abundances determined when they...
use their new calibrations. However, such a point of view is somewhat problematic, as it assumes that all galaxies follow the same chemical evolutionary pattern, independently of their mass or morphology, and it assumes no evolution with redshift, while these are two assumptions that need to be verified separately. Moreover, other researchers in the field (e.g., Tremonti et al. 2004; Izotov et al. 2006) that also thoroughly tested the empirical methods using SDSS data, have demonstrated that in general new empirical relations show results that are in good agreement with what was found before. For these reasons, but also for comparison sake with what was done in Coziol et al. (1999), we choose for our study to apply the same empirical relations that were used before, but limit our chemical study to the two most important abundance ratios, O/H and N/O, which were shown by Izotov et al. (2006) to be less dependent on the method adopted to determine the gas temperature.

Another important difficulty encountered in chemical evolution studies of SFGs is related with the contamination of emission lines by absorption features produced by the underlying older stellar populations. In our research, we have solved this problem by subtracting a stellar population template from each spectrum, as determined by the spectral synthesis code STARLIGHT (Cid Fernandes et al. 2005). This method also has the advantage that through the fitted templates the star formation histories (SFHs) of the SFGs can be deduced, and other metallicity-independent parameters like the stellar velocity dispersion, which combined with the effective radius can yield an estimate of the mass of the bulge. In our study, we use this new information in parallel with the morphologies which were determined independently to complete our view about the chemical evolution and formation process of SFGs in the nearby universe.

This study is organized in the following manner. In Section 2, we describe how our sample of SFGs was constructed and how the data for our analysis were obtained. In Section 3, we present our results for the chemical abundances and show how they varied with the mass and morphology of the galaxies. In the same section, we also explore the relation between the chemical abundances and the SFHs, and compare our results using STARLIGHT with some relevant models from Starburst99. In Section 4, we discuss our observations and propose a new interpretation. Our main conclusion can be found in Section 5. Many of our results were verified using statistical tests, which are regrouped in the Appendix.

2. DETERMINATION OF THE SAMPLES AND DATA FOR ANALYSIS

The data for our study were taken from the SDSS Data Release 7 (Abazajian et al. 2009). Using the STARLIGHT Virtual Observatory service\(^1\)\(^1\) we retrieved the spectroscopic data for 122,751 SFGs, with emission lines having a signal-to-noise ratio (S/N) \(> 3\) (adjacent continuum S/N \(> 10\)) and a redshift \(z \leq 0.25\). The spectra were corrected for Galactic dust extinction and processed through STARLIGHT spectral synthesis code (Cid Fernandes et al. 2005), producing for each galaxy a stellar population template-corrected spectrum from which emission line fluxes were measured automatically. Note that STARLIGHT estimates and applies a correction for internal dust extinction (Asari et al. 2007), which means that the stellar population templates, and the SFH deduced from these templates, as well as the template-subtracted emission spectra, are free of this effect.

In SDSS, the fibers have a fixed aperture and are centered on the nucleus of the galaxies. Comparing the physical projection of this aperture on the sky with the efficient radius as determined by Simard et al. (2011), we found that, except at very low redshifts, the spectra always cover the same physical regions comparable with the sizes of the bulges of the galaxies. This implies that our stellar population study and chemical analysis are mostly concerned with processes affecting the bulges of the galaxies.

2.1. Separation between SFGs and AGNs

The SFG classification presented in Figure 1 is based on one diagnostic diagram (Baldwin et al. 1981; Veilleux & Osterbrock 1987), where we have applied the separation criterion between active galactic nuclei (AGNs) and SFGs proposed by Kauffmann et al. (2003). According to the standard interpretation of stellar ionized H\(\text{II}\) regions (McCall et al. 1985; Evans & Dopita 1985; Coziol 1996), the SFGs trace a sequence of increasing metallicity as the emission ratio\(\frac{[\text{O}\text{\,III}] \, \lambda 5007}{H\beta}\) decreases, which is produced by the cooling effect of oxygen. Similarly, the abundance of nitrogen is also expected to grow in the same direction, as the ratio\(\frac{[\text{N}\text{\,II}] \, \lambda 6584}{H\alpha}\) increases (Thurston et al. 1996; van Zee et al. 1998).

Consistent with the standard interpretation, Coziol et al. (1999) have determined that some SFGs, especially those experiencing a starburst in their nuclear regions, present an excess of nitrogen abundance compared to the expected chemical evolution sequence traced by H\(\text{II}\) regions in late-type spirals. This is illustrated in Figure 2(a), where we show the results of two ionization models as produced by Coziol et al. (1999): for the same metallicity, galaxies following the Sequence 2 (Seq. 2) have a nitrogen abundance about 0.2 dex higher than galaxies following the Sequence 1 (Seq. 1). Figure 2 reveals that most of the SFGs in our sample have a data point that falls be-
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Figure 2. Same as Figure 1 using different separation criteria: (a) according to Coziol et al. (1999) models of H II regions, where Seq. 1 is a standard H II region abundance model, and Seq. 2 is a similar model including an excess in nitrogen abundance by 0.2 dex—the median of these models (bold dashed curve) separates nitrogen-poor from nitrogen-rich SFGs; (b) according to an alternate criterion to separate SFGs from AGNs, as proposed by Stasinska et al. (2006).

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Between these two models. Using the median of these two models, we have thus separated our SFG sample into two groups (see Figure 2(a)). The SFGs that are nitrogen poor are identified as SFG 1 and represent 55.2% of the sample, while those that are nitrogen rich are identified as SFG 2 and represent 44.8%.

In Figure 2(a), we note that the path of Seq. 2 seems to form an upper limit rather than a median as was determined by Coziol et al. (1999). The reason for this difference is because in 1999 the concept of transition objects, which are defined roughly as galaxies where both an AGN and intense star-forming activity are present, was not applied systematically in classification studies, and the limit between SFGs and AGNs was then located at higher values of the ratio [N II] λ6584/ Hα. Although Coziol et al. (1999) in their analysis presented evidence against the presence of an AGN in their sample, this possibility remains in this much larger and differently selected sample. Therefore, the SFG 2 galaxies may show an excess of excitation due to an AGN instead of an excess of nitrogen abundance. Interestingly, in Figure 2(b) we can see that the median of the two abundance models defined in (a) almost coincides with a different separation criterion between SFGs and AGNs which was previously proposed by Stasinska et al. (2006).

If we use this distinction we could separate our sample into two different new groups, according to which 64.8% of the galaxies are pure SFGs (SFG 3), and the rest (35.2%) are AGNs (SFG 4).

For our sample of SFGs we have therefore identified two different interpretations for the increase of nitrogen emission in the standard diagnostic diagram. The first one suggests that some SFGs show an excess in nitrogen abundance, the other suggests an excess in emission due to a supplementary source of ionizing photons, consistent with a central AGN. In order to discriminate which of these two hypothesis is the most probable, we here present the results of two tests. The first test, which was devised by Coziol et al. (1999), consists of comparing the ratio [N II] λ6584/ Hα with the ratio [S II] λλ6717,6731/ Hα. The principle of this test is that if there is an excess of excitation, this excess should appear in both line ratios at the same time.

As a second test, we present in Figure 4(a) for the SFG 1 and SFG 2 and in Figure 4(b) for the SFG 3 and SFG 4 the graph of the Hα luminosity as a function of the continuum at 4800 Å. The continuum fluxes were measured in the raw spectra, that is, before they were treated by STARLIGHT, and were only corrected for Galactic extinction. The principle of this test is based on a suggestion made by Osterbrock (1989), according to whom the linear relation (in log) between the two luminosities must be different for galaxies excited by AGNs and galaxies excited by stars, because of the different power laws in these objects relating the continuum with the ionizing flux. In Figure 4, we observe that the linear relations for our four SFG groups have almost the same slopes. These linear relations have extremely high factors of correlation (see Table 1). For comparison we have traced the relation found for two sample of SDSS AGNs classified as Seyfert 2 and LINERs (Torres-Papaqui et al. 2012). The slopes of the linear relations for the SFGs are significantly shallower than for those measured in AGNs. From this
Figure 3. Excitation test, to check for the presence of AGNs, as proposed by Coziol et al. (1999). The lower left boxes contain galaxies with a normal level of excitation (due to massive stars), while galaxies showing an excess of excitation in both lines fall out of the limits of these boxes. The four subsamples correspond to nitrogen-poor SFGs (SFG 1) vs. nitrogen-rich SFGs (SFG 2), according to Coziol et al. (1999), and pure SFGs (SFG 3) vs. AGNs (SFG 4) according to Stasinska et al. (2006).

Figure 4. Second test for the presence of AGN based on the relations between the logarithm of the luminosity of the continuum ($L_{\text{FC}}$) and the logarithm of the luminosity of the ionized gas ($L_{\text{H}\alpha}$): (a) results for the SFG 1 and SFG 2 samples; (b) results for SFG 3 and SFG 4 samples. The significantly steeper linear relations for the Seyfert 2 and LINERs were determined by Torres-Papaqui et al. (2012). For numerical values see Table 1.

second test we conclude, once again, that there is no evidence for the presence of an AGN in our sample of SFGs.

Taking into account the high level of consistency of the above two tests, we conclude that in general we see no evidence for AGNs in our sample of SFGs, and we find consequently no reason to change our classification based on the separation criterion proposed by Kauffmann et al. (2003). For the remaining of our analysis we will keep only the distinction between nitrogen-poor (SFG 1) and nitrogen-rich (SFG 2) SFGs.

2.2. Determination of Abundances and Physical Parameters

Once the possibility of an AGN as a source of ionization for the gas is eliminated, standard methods for H\textsc{ii} regions can be applied to determine the chemical abundances of the
For the nitrogen abundance, $N/\sigma$ in Vacca & Conti (1992), which yields values with a typical uncertainty of the order of ±0.2 dex (Edmunds & Pagel 1984). For the nitrogen abundance, $N$, we used the method described in Vacca & Conti (1992), which yields values with a typical uncertainty of the order of ±0.2 dex (Edmunds & Pagel 1984).

For the metallicity, $O/H$, we used the method described in Vacca & Conti (1992), which yields values with a typical uncertainty of the order of ±0.2 dex (Edmunds & Pagel 1984).

For the nitrogen abundance, $N$, we used the method described in Vacca & Conti (1992), which yields values with a typical uncertainty of the order of ±0.2 dex (Edmunds & Pagel 1984). For the nitrogen abundance, $N$, we used the method described in Vacca & Conti (1992), which yields values with a typical uncertainty of the order of ±0.2 dex (Edmunds & Pagel 1984).

The probability of correlation by chance is practically 0 for all the tests.

Table 1

| Sample   | Slope   | Spearman | Pearson |
|----------|---------|----------|---------|
| SFG 1    | 1.10 ± 0.05 | 0.883 | 0.891 |
| SFG 2    | 1.14 ± 0.03 | 0.932 | 0.932 |
| SFG 3    | 1.11 ± 0.05 | 0.877 | 0.886 |
| SFG 4    | 1.13 ± 0.03 | 0.931 | 0.931 |
| Seyfert 2| 1.48 ± 0.03 | 0.810 | 0.829 |
| LINER    | 1.45 ± 0.03 | 0.739 | 0.773 |

Note. The probability of correlation by chance is practically 0 for all the tests.

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3. RESULTS

3.1. Variation of Abundances, and Relation with Mass and Morphology

In Figure 5, we trace the abundance of nitrogen as a function of the metallicity, distinguishing between nitrogen-poor (SFG 1) and nitrogen-rich (SFG 2) SFGs. Overplotted on this figure we show the two abundance sequence models obtained by Coziol et al. (1999). Also shown are the relations for the different closed-box chemical evolutionary models for the production of nitrogen as proposed by Vila-Costas & Edmunds (1993): the secondary and the primary + secondary models. In general, the SFG 1 seems to follow the secondary enrichment model. This is obviously not the case for the SFG 2, however, which for the same value in log (O/H) show an excess of nitrogen, on average of 0.15 dex, compared to the SFG 1.

In Figure 5(b), we also note a remarkable feature: the chemical enrichment process for the SFG 2 is not continuous—we observe an abrupt jump by 0.3 dex in nitrogen at a metallicity log (O/H) = −3.4 (almost the solar metallicity). The reason why

Table 2

| Hubble | E | E/S0 | S0 | S0/Sa | Sa | Sab | Sb | Sbc | Sc | Scd | Sd | Sdm | Im |
|--------|---|------|----|-------|----|-----|----|-----|----|-----|----|-----|----|
| de Vaucouleurs | −6 to −4 | −3 to −1 | 0 | . . | 1.0 | . . | 3.0 | . . | 5.0 | . . | 7.0 | 8.0 to 9.0 | 10 to 11 |
| This work   | −5 | −2 | 0 | 0.5 | 1.0 | 2.0 | 3.0 | 4.0 | 5.0 | 6.0 | 7.0 | 9.0 | 10.0 |

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Figure 5. Nitrogen abundance as a function of metallicity: in (a) the SFGs poor in nitrogen (SFG 1), and in (b) the SFGs rich in nitrogen (SFG 2). Also shown are the closed-box chemical evolution models proposed by Vila-Costas & Edmunds (1993): the secondary model (dashed line) and the primary + secondary model (continuous curve). The two other curves trace the sequences obtained in Coziol et al. (1999). In (c) and (d) we show the same results relative to the secondary relation for nitrogen enrichment, with their respective medians.

we note this particularity is because exactly the same observation was done before by Coziol et al. (1999) for their comparatively small sample of about 100 UV bright SBNGs. The fact that exactly the same feature appears in our significantly larger sample and generally selected sample (no other criterion other than the SFG classification was applied) is quite remarkable. It suggests that this feature must be a characteristic of SFGs (it affects 45% of all the galaxies in our sample) and not a peculiar trait of starburst galaxies. This phenomenon must be related consequently to some common mechanism or event occurring during the chemical evolution of all these galaxies.

In Figure 5(a), although the nitrogen distribution for the SFG 1 fits the secondary relation, we may detect a slight trend toward relatively high nitrogen abundance also in this sample. This is better perceived in Figure 5(c) where we have plotted over the data the medians of the difference in nitrogen abundance relative to the secondary relation. In Coziol et al. (1999), the UV bright starburst galaxies were showing a trend toward a decrease in the excess of nitrogen at high metallicity. The same trend may also be visible in Figure 5(d) for the SFG 2, although, from the medians, we conclude that the decrement is much weaker than what was observed in Coziol et al. (1999).

In Figure 6, we trace the metallicity and nitrogen offset from the secondary relation as a function of the absolute magnitude in $B$. In Figures 6(a) and (b), we have included the luminosity–metallicity relation as determined by Tremonti et al. (2004) for their sample of 53,400 SDSS SFGs (correcting for the Hubble constant used in our study). Our samples taken as a whole (adding the SFG 1 with the SFG 2) are in good agreement with this relation. However, when we introduce the distinction between nitrogen-rich and nitrogen-poor SFGs we obtain a different perspective. The metallicity of the SFG 1 increases with the mass more rapidly than the relation found by Tremonti et al. (2004), while it increases less rapidly in the SFG 2. In fact, and as the correlation tests in Table 3 are confirming, the metallicity of the SFG 2 stays almost constant. Therefore, it is likely that the SFG 2 become deficient in oxygen as the mass increases. This is verified in Figure 7, which shows the different histograms for the metallicities and absolute magnitudes. Although the SFG 2 are on average more massive (more luminous in $B$) than the SFG 1, their peak in metallicity lies at a lower value than in the SFG 1. This confirms that the SFG 2 are relatively deficient in oxygen compared to the SFG 1. Note that the same phenomenon was also observed by Coziol et al. (1997) for the same sample of

Table 3

| Pairs                  | $r$    | $P(r)$ | $r_s$  | $P(r_s)$ |
|-----------------------|--------|--------|--------|----------|
| $M_B$ vs. [O/H] (SFG 1)| -0.4091| 0.0450 | -0.4369| 0.0445   |
| $M_B$ vs. [O/H] (SFG 2)| -0.1376| 0.4893 | -0.1390| 0.5143   |
| $M_B$ vs. Δ(N/O) (SFG 1)| -0.2016| 0.3652 | -0.2160| 0.3865   |
| $M_B$ vs. Δ(N/O) (SFG 2)| -0.0638| 0.5964 | -0.0842| 0.5643   |
UV-bright starburst galaxies that were shown later to be nitrogen rich (Coziol et al. 1999). So it seems now that the two phenomena must be somehow connected.

In Figure 6(c), we find that the excess of nitrogen in the SFG 1 is slightly increasing with the mass (although in Table 3 we have a 36%–38% chance that the correlation is spurious). On the other hand, in Figure 6(d) for the SFG 2 the excess stays constant independently of the mass. This is confirmed by the correlation tests (Table 3). It seems therefore likely that the chemical abundances in the SFG 2 reach some sort of physical limit connected with the masses of the galaxies.

In Figure 8, we compare the results obtained for the morphologies, the mean stellar population ages, the masses of the bulges, and absolute magnitudes in $B$, as measured in the SFG 1 and SFG 2 samples. The box-whisker diagrams show that the SFG 2 have earlier types (Figure 8(a)) and older stellar populations than the SFG 1 (Figure 8(b)). The masses of the bulges in Figure 8(c) are also increasing in the SFG 2, which is consistent with the earlier morphologies. The difference in absolute magnitude in $B$ (Figure 6(d)) also implies higher masses for the SFG 2 as compared to the SFG 1. All the above differences were confirmed at a level of confidence of 95% by statistical tests (see Figure 22 in the Appendix). All these variations and differences point toward a connection between the chemical evolution process and the formation process of the SFGs.

3.2. Analysis of SFH Using STARLIGHT

Through the fitting templates using STARLIGHT we have deduced the history of star formation (SFH) for all the galaxies in our sample. In order to investigate how the chemical evolution in the SFGs correlates with their SFHs, we have separated the diagram of abundances in Figure 9 in four subsamples with increasing metallicity. In each metallicity bin we further distinguish between low and high nitrogen abundance, obtaining in total eight different subsamples. The corresponding SFHs for these eight subsamples are shown in Figure 10. The median physical characteristics of the galaxies in each subsample are reported in Table 4 for the SFG 1 and in Table 5 for the SFG 2.

The SFH describes how the star formation rate (SFR) of a galaxy varied over its lifetime. In particular, the SFH allows us to distinguish between galaxies that have experienced more or less constant star formation rates (CSFR), as is expected for late-type spirals, and galaxies in a present starburst phase (SBP). Galaxies with CSFRs have a flat SFH (e.g., subsamples 4 and 8 in Figure 10) while galaxies in SBP, with recent SFR higher than in its past, have a negative SFH slope (e.g., subsamples 1 and 5 in Figure 10). Consequently, a galaxy with a positive SFH slope would have formed most of its stars in the past, as expected for early-type spirals and ellipticals (no case is observed in our sample). The SFH also yields information about the intensity of star formation: for any interval of time the SFR corresponds to the median, which implies that the higher the median the more intense the star formation at this time; consequently, the higher the intensity of star formation and the higher the mass of stars formed, which is equal to the surface below the curve.

For the SFG 1 sample in Figure 10 (left panels) we observe that almost all the galaxies with low nitrogen abundance (in subsamples 1, 2, and possibly 3) show some evidence of recent
Figure 7. Histograms for the metallicities and absolute magnitudes in the SFG 1 and SFG 2.

Table 4
Physical Characteristics of SFG 1 as Divided by Metallicity Intervals

| Bin ID | Number of Galaxies | Range in log([O/H]) | Range in log(N/O) | $T$ | $\log(M_{\text{bulge}}/M_\odot)$ | $\log(M_{\text{bulge}}/M_\odot)$ | $M_B$ |
|--------|-------------------|--------------------|------------------|-----|-------------------------------|-------------------------------|------|
| 1      | 1759              | $-3.85 \leq x \leq -3.55$ | $-1.85 \leq y \leq -1.40$ | 6.0 | 7.88                          | 9.42                          | -17.81 |
| 2      | 11375             | $-3.55 \leq x \leq -3.25$ | $-1.60 \leq y \leq -1.15$ | 6.0 | 8.25                          | 9.44                          | -18.14 |
| 3      | 25561             | $-3.25 \leq x \leq -2.95$ | $-1.25 \leq y \leq -0.80$ | 6.0 | 8.44                          | 9.55                          | -18.84 |
| 4      | 13697             | $-2.95 \leq x \leq -2.65$ | $-1.05 \leq y \leq -0.60$ | 5.0 | 8.53                          | 9.66                          | -19.36 |
| 5      | 2175              | $-3.85 \leq x \leq -3.55$ | $-1.40 \leq y \leq -0.95$ | 6.0 | 7.99                          | 9.46                          | -18.24 |
| 6      | 5403              | $-3.55 \leq x \leq -3.25$ | $-1.15 \leq y \leq -0.75$ | 6.0 | 8.32                          | 9.51                          | -18.66 |
| 7      | 5739              | $-3.25 \leq x \leq -2.95$ | $-0.80 \leq y \leq -0.35$ | 4.0 | 8.62                          | 9.75                          | -19.42 |
| 8      | 3156              | $-2.95 \leq x \leq -2.65$ | $-0.60 \leq y \leq -0.15$ | 4.0 | 8.68                          | 9.77                          | -19.47 |

Table 5
Physical Characteristics of SFG 2 as Divided by Metallicity Intervals

| Bin ID | Number of Galaxies | Range in log([O/H]) | Range in log(N/O) | $T$ | $\log(M_{\text{bulge}}/M_\odot)$ | $\log(M_{\text{bulge}}/M_\odot)$ | $M_B$ |
|--------|-------------------|--------------------|------------------|-----|-------------------------------|-------------------------------|------|
| 1      | 41                | $-3.85 \leq x \leq -3.55$ | $-1.85 \leq y \leq -1.40$ | 6.0 | 7.82                          | 9.52                          | -18.23 |
| 2      | 207               | $-3.55 \leq x \leq -3.25$ | $-1.60 \leq y \leq -1.15$ | 5.0 | 8.68                          | 9.57                          | -18.08 |
| 3      | 9214              | $-3.25 \leq x \leq -2.95$ | $-1.25 \leq y \leq -0.80$ | 5.0 | 8.53                          | 9.59                          | -19.17 |
| 4      | 5544              | $-2.95 \leq x \leq -2.65$ | $-1.05 \leq y \leq -0.60$ | 4.0 | 8.62                          | 9.69                          | -19.46 |
| 5      | 590               | $-3.85 \leq x \leq -3.55$ | $-1.40 \leq y \leq -0.95$ | 5.0 | 7.87                          | 9.61                          | -18.83 |
| 6      | 3327              | $-3.55 \leq x \leq -3.25$ | $-1.15 \leq y \leq -0.75$ | 5.0 | 8.47                          | 9.63                          | -18.86 |
| 7      | 30201             | $-3.25 \leq x \leq -2.95$ | $-0.80 \leq y \leq -0.35$ | 4.0 | 8.71                          | 9.75                          | -19.36 |
| 8      | 5863              | $-2.95 \leq x \leq -2.65$ | $-0.60 \leq y \leq -0.15$ | 4.0 | 8.72                          | 9.78                          | -19.42 |
Figure 8. Box-whisker plots comparing the characteristics of the galaxies in the SFG 1 and SFG 2 samples: (a) morphologies; (b) mean stellar population ages; (c) bulge masses; and (c) absolute magnitudes in $B$. The points correspond to the means. Notches (barely visible due to the large size of the samples) that intersect suggest no significant difference in median.

Figure 9. Variation of abundances, where we have separated the whole sample in four subsamples with increasing metallicity. In each subsample we further distinguish between low (subsamples 1, 2, 3, and 4) and high (subsamples 5, 6, 7, and 8) nitrogen abundances.
bursts of star formation. For the SFG 1 that are rich in nitrogen, we observe a transition to constant star formation starting with subsamples 7 (galaxies in subsamples 5 and 6 are still in bursts). In the SFG 2 (right panels in Figure 10), the sharp increase in nitrogen abundance seems connected with intense (more intense than in the SFG 1) bursts in star formation (subsamples 1, 5, and 6). We also note that the transition to constant star formation appears earlier than in the SFG 1, in subsample 2 instead of 3. In general, we observe that galaxies having higher intensity bursts or higher SFR at any time end up with higher nitrogen abundance (comparing the continuous curves with the dashed ones). However, the difference seems to decrease at high metallicity (e.g., subsamples 4 and 8 in both the SFG 1 and SFG 2 samples).

The box-whisker plots for the SFG 1 in Figure 11 and for the SFG 2 in Figure 12 are consistent with our previous analysis based on the abundances (see also Tables 3 and 4). In both samples, we observe a change toward earlier-type morphology and older stellar populations as the metallicity and nitrogen increases. We also observe an increase in bulge mass and total mass. In general, the more massive and early-type SFGs with low metallicity are those that are experiencing more intense bursts, and at high metallicity the more massive and early-type SFGs are also those that have experienced higher level of star formation in the past. All these differences were confirmed by statistical tests in the Appendix (see Figures 23 and 24).

3.3. Comparison with Starburst99 Models

The results of our analysis based on STARLIGHT were compared using the model for SFGs Starburst99 (Leitherer 1999).\(^3\) We used some of the original 1999 data set, considering only instantaneous or constant star formation scenarios, and have run a few more models using the WINDOWS version of the software. The main goal of this comparison is to verify if we can obtain Starburst99 models that are consistent with our STARLIGHT analysis, in particular, by isolating the galaxies that show recent starbursts. Note that we did not perform an exhaustive study using Starburst99 because this would have fall well beyond the limits of the present study. However, we have found that just a few simple modifications to the parameters of the original data set were sufficient to yield results in good agreement with STARLIGHT.

The only two parameters produced by Starburst99 that can be compared with our results from STARLIGHT are the H$\alpha$ equivalent width and absolute magnitude in B. The first parameter is a good indicator for star formation over short timescales, for this is the ratio of the flux in emission with the flux in the continuum. As we already mentioned, the second parameter is a good indicator for star formation over longer timescales (0.5–6 Gyr) and a reasonable proxy for the total mass of galaxies. In Figure 13, we show the predictions of instantaneous burst models, having different powers of the IMF ($\alpha$) and upper mass limit ($M_{\text{up}}$); the Salpeter IMF corresponds to $\alpha = 2.35$, and only two mass limits were tested, 30 and 100 $M_\odot$. The data presented are the medians and percentiles as measured in the galaxies found in the abundance subsamples defined in Figure 9. It is obvious that the absolute magnitudes of the SFGs are too high to be reproduced by an instantaneous burst scenario. This result clearly suggests that in these galaxies star formation happened over longer timescales.

The next series of models in Figure 14 are for constant star formation. The first good fits are obtained with a steeper IMF than Salpeter, $\alpha = 3.30$, and upper mass limit $M_{\text{up}} = 100 M_\odot$. But then we lose most of the SFGs that STARLIGHT was identifying as starbursts. Based on this series of models it becomes obvious in which direction we need to modify the parameters to obtain fits that are consistent with STARLIGHT analysis. The IMF has to become steeper still, implying that there are less massive stars and more intermediate-mass stars ionizing the gas in these galaxies (more B than O stars). But then to compensate, the total amount of ionizing photons produced has also to be higher, which justify the upper mass limit $M_{\text{up}} = 100 M_\odot$. Our two best fits, which yield almost a one-to-one relation with the STARLIGHT results, are presented in Figure 15. They have $M_{\text{up}} = 100 M_\odot$ and an IMF varying from $\alpha = 4.00$ ((a) and (d)) to $\alpha = 4.10$ ((b) and (e)). On the other hand, none of these models reproduce the trend in metallicity we observed.

Based on our comparison, we do not claim we have determined that the IMF in the SFGs is much steeper than Salpeter or that the upper mass limit is 100 $M_\odot$. What we suggest, rather, is that the results of Starburst99 that are most consistent with STARLIGHT imply recent bursts of star formation happening over a background of constant star formation. But considering that constant star formation in galaxies can easily be reproduced by a sequence of instantaneous bursts (Leitherer 1999), it therefore seems that the best scenario that the models of Starburst99, consistent with STARLIGHT, imposes on the data.

\(^3\) http://www.stsci.edu/science/starburst99/docs/default.htm
Figure 11. Box-whisker plots for the eight SFG 1 subsamples, as defined in Figure 9(a). We compare (a) the morphologies, $T$; (b) the mean stellar ages, $t_{\text{star}}$; (c) the bulge masses; and (d) the absolute magnitudes in $B$. The diamond points with error bars correspond to the means. Notches that intersect suggest no significant difference in median.

Figure 12. Same as in Figure 11 for the eight SFG 2 subsamples as defined in Figure 9(b).
can be, for both SFGs, a sequence of bursts of star formation over a relatively long period of time. Similar results were obtained before in starburst studies such as Goldader et al. (1997) and Coziol et al. (2001). There is also now mounting evidence that typical starburst galaxies, like M 82, have experienced more than one burst spread both in time and space (de Grijs et al. 2001; Smith & Gallagher 2001; Förster Schreiber et al. 2003a, 2003b; Smith et al. 2006; Mayya et al. 2006; Strickland & Heckman 2009). That this scenario applies in general to starburst galaxies was already verified by Coziol et al. (2001). These last authors even confirmed the dominant presence of B-type stars in the ionizing regions of these galaxies, which is a natural consequence of a sequence of bursts over a few Gyr period (Coziol 1996).

From our comparison with Starburst99 models we conclude that our STARLIGHT analysis (except for the metallicity) yields results that are consistent in all the SFGs with a sequence of bursts of star formation over a long period of time (of Gyr scale).

4. DISCUSSION

In Coziol et al. (1999), the authors suggested that the discontinuous pattern observed in the diagram of nitrogen versus metallicity was the result of a special mode of star formation in starburst galaxies. Assuming these galaxies experienced a succession of bursts over a few Gyr period, decreasing in intensity with time, and assuming a time delay between the production of oxygen by massive O and B stars and the production of nitrogen by intermediate-mass stars (Garnett 1990), then the higher the intensity of the first bursts, the higher the increase of nitrogen compared to the oxygen.

Although our present observations seem to be in good agreement with the above starburst scenario, our new analysis

**Figure 13.** Results of Starburst99 models assuming instantaneous bursts with different IMF powers and upper mass limits. The data correspond to the medians and percentiles as measured in the subsamples in metallicity as defined in Figure 9 (identified by their numbers).
proposes a slightly different interpretation. First, our sample of SFGs is more general than the sample defined in Coziol et al. (1999). The only criterion applied in the selection of the galaxies is that they must not show any evidence of ionization from an AGN. Second, our analysis of the SFHs produced by STARLIGHT suggests that there is no dichotomy in the star-forming mode of the SFGs, that is, all the SFGs follow the same star formation pattern, consistent with a sequence of bursts of star formation over a period of a few Gyr. The comparison of our STARLIGHT analysis with Starburst99 models is extremely compelling on this point. What our new analysis suggests, therefore, is that the nitrogen excess is not an anomaly related to some special galaxies like starbursts, but is more likely a typical characteristic of SFGs in the nearby universe. This also implies that the phenomenon that creates the excess of nitrogen must be extremely common in SFGs, although possibly more obvious in starburst galaxies.

Consistent with the above interpretation, we believe that the common phenomenon responsible for the depletion of oxygen and relative increase in nitrogen as observed in the SFGs could be starburst winds (Heckman et al. 1990; Lehnert & Heckman 1996). In particular, this mechanism is suspected to be the main phenomenon responsible for increasing the abundance of metals in the intergalactic medium (see Veilleux et al. 2005 and references therein). Now, it is easy to adapt the model of a sequence of bursts as proposed by Coziol et al. (1999) including as a major component the effect of starburst winds. We assume that a starburst wind in a region is effective (that is, capable of ejecting metals out of the region) only for a short period of time, of the order of a few $10^7$ yr (as is confirmed using Starburst99). Consequently, the main effect of this wind would be to preferentially deplete the region of the chemical components produced by massive stars (mostly oxygen, neon, iron, but also sulfur, argon, and calcium; see

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**Figure 14.** Results of Starburst99 models assuming continuous star formation with different IMF powers and upper mass limits. The data correspond to the medians and percentiles as measured in the subsamples in metallicity as defined in Figure 9 (identified by their numbers).
Strickland & Heckman 2009 and references therein for a full discussion of starburst wind loads). Then, when intermediate stars begin producing nitrogen, a few $10^8$ yr after the beginning of the burst, the intensity of the wind would already be too low to have a significant impact on the abundance. Moreover, within the sequence of bursts model we do not expect the next generation of bursts to affect the nitrogen abundance in the region, simply because these bursts will happen in different regions, considering that in such a brief interval of time, a few $10^8$ yr, the conditions in a region that suffered a burst would not be favorable for another one. However, these conditions could easily become favorable in another nearby region, consistent with the propagation of star formation hypothesis; after $10^8$ yr active star formation regions would have propagated a few kiloparsecs from the first burst region (see, for example, Nomura & Kamaya 2001 and references therein).

Can we verify the starburst wind hypothesis directly with our observations? To answer this question we refer to the detailed calculation made by Strickland & Heckman (2009), according to whom the difference between the nitrogen-rich and nitrogen-poor SFGs should depend on the intensity of the bursts. In their model, a starburst wind is considered to be effective above an intensity of $0.04 M_\odot \, yr^{-1} \, kpc^{-2}$ (Lehnert & Heckman 1996; Heckman 2003). Using STARLIGHT we have estimated the intensity of the bursts (see Table 6) for the galaxies in both samples showing the higher recent SFR (subsamples 1 and 5). In Figure 16, we show the corresponding box-whisker plots. We see that the intensity of the bursts in the galaxies with the most obvious excess of nitrogen (the SFG 2 in subsample 5) is significantly higher than in galaxies without an excess (SFG 1). Also shown in this figure is the threshold calculated by Strickland & Heckman (2009). The median and
average of the SFG 2 are well above this limit. Note that we should not expect a clear cut distinction, considering that these bursts are only the most recent of a series. However, statistically the difference is significant and in good agreement with the bursts are only the most recent of a series. However, statistically should not expect a clear cut distinction, considering that these average of the SFG 2 are well above this limit. Note that we masses of the galaxy (Goldader et al. 1997; Coziol et al. have established another link between the chemical evolution 2001). Also consistent with this difference of characteristic, the STARLIGHT analysis in Figure 10 reveals that in the past the SFG 2 have also experienced more intense star-forming episodes than the SFG 1. All these differences were found to be significant using statistical tests (see Figure 25 in the Appendix). In general, our results are quantitatively consistent with the predictions made by the starburst wind model.

On the other hand, one observation seems somewhat counterintuitive in regard to the starburst wind hypothesis. Many authors have discussed and concluded that the higher the mass of a galaxy and the more difficult it should be for this system to loose metals through starburst winds (e.g., Tremonti et al. 2004). Yet, our observations show no evidence of such trend. In Figure 6(d) for the SFG 2 the excess of nitrogen stays constant independently of the mass, and in Figure 6(c) we may even detect an increase of nitrogen with the mass in the SFG 1. On this matter, our analysis of STARLIGHT results in parallel with our determination of the morphologies and mass of the bulges is quite revealing. It allows us to connect the excess of nitrogen with massive galaxies, having developed massive bulges and earlier-type morphologies. At the same time it shows that the star formation in the past of these galaxies was more intense than in those without the nitrogen excess. There is consequently a very strong relation with the formation process of the galaxies. This may suggest that the abundance differences observed between the SFG 2 and SFG 1 took place mostly during the formation process of these galaxies. This could have happened when the gravitational potential wells of these galaxies were less massive, because they were still growing in size, making the intense starburst winds slightly more efficient and independent of the final, present mass.

Consistent with the formation hypothesis, it was recently reported by Pilyugin & Thuan (2011) that the SFGs are showing evidence for downsizing, which states that massive galaxies formed at higher redshifts than smaller mass galaxies. If we can find such evidence in our sample of galaxies, consistent with the scenario we proposed for the excess of nitrogen, then we would have established another link between the chemical evolution and the formation process of these galaxies.

To test the downsizing hypothesis in our sample we have separated the SFG 1 and SFG 2 samples in nine redshift subsamples increasing by 0.025. The different bin ranges are given in Table 7 for the SFG 1 and Table 8 for the SFG 2, together with the number of galaxies in each redshift subsample. Note that our limit in redshift is lower than in Pilyugin & Thuan (2011), $z = 0.25$ instead of $z = 0.4$. In Figure 17, we show the box-whisker plots for the variations of the properties of the SFG 1 as divided by redshift intervals. This is not observed however in the SFG 2 sample, where the metallicity and nitrogen excess stay almost constant (see Figures 26 and 27 in the Appendix for confirmation by statistical tests). Note that this difference between the SFG 1 and SFG 2 goes against what would be expected if the variations observed were due to an aperture effect—the same effect should have

| Sample | Min | 1Q | Median | Mean | 3Q | Max |
|--------|-----|----|--------|------|----|-----|
| SFG 1 (1) | 0.002 | 0.020 | 0.032 | 0.040 | 0.051 | 0.351 |
| SFG 1 (5) | 0.002 | 0.020 | 0.036 | 0.048 | 0.062 | 0.395 |
| SFG 2 (1) | 0.009 | 0.024 | 0.040 | 0.054 | 0.059 | 0.257 |
| SFG 2 (5) | 0.002 | 0.029 | 0.062 | 0.080 | 0.105 | 0.509 |

| $M_B$ |
|-------|
| 22.79 |
| 18.39 |
| 17.72 |
| 17.81 |
| 17.19 |
| 16.02 |

| Table 6
Intensity of Star Formation and Absolute Magnitude of SFGs Showing Evidence of Recent Bursts

| Sample | SFR/Area | $M_B$ |
|--------|----------|-------|
| SFG 1 (1) | 0.002 | 19.77 |
| SFG 1 (5) | 0.002 | 20.00 |
| SFG 2 (1) | 0.009 | 22.79 |
| SFG 2 (5) | 0.002 | 20.42 |

| Table 7
Physical Characteristics of SFG 1 as Divided by Redshift Intervals

| Bin | Range in $z$ | Number of Galaxies | $T$ | $\log(\frac{M_{\text{bulge}}}{M_\odot})$ | $\log(\frac{M_B}{M_\odot})$ | $M_B$ |
|-----|-------------|-------------------|-----|----------------------|----------------------|-------|
| 1   | $0.05 < z \leq 0.075$ | 17878 | 5.0 | 8.10 | 9.22 | 17.86 |
| 2   | $0.075 < z \leq 0.125$ | 19718 | 5.0 | 8.28 | 9.47 | 18.04 |
| 3   | $0.125 < z \leq 0.175$ | 13479 | 5.0 | 8.31 | 9.64 | 18.21 |
| 4   | $0.175 < z \leq 0.225$ | 8037 | 5.0 | 8.31 | 8.92 | 18.37 |
| 5   | $0.225 < z \leq 0.250$ | 4682 | 5.0 | 8.25 | 9.94 | 18.53 |
| 6   | $0.250 < z \leq 0.300$ | 1741 | 5.0 | 8.21 | 10.08 | 18.70 |
| 7   | $0.300 < z \leq 0.350$ | 819 | 5.0 | 8.10 | 10.20 | 18.86 |
| 8   | $0.350 < z \leq 0.400$ | 406 | 5.0 | 8.08 | 10.26 | 19.02 |
| 9   | $0.400 < z \leq 0.450$ | 98 | 5.0 | 7.99 | 10.31 | 19.18 |
Table 8
Physical Characteristics of SFG 2 as Divided by Redshift Intervals

| Bin ID | Range in $z$ | Number of Galaxies | $T$ | $\log(\frac{M_{\text{bulge}}}{M_{\odot}})$ | $\log(\frac{M_{\text{bulge}}}{M_{\odot}})$ | $M_B$ |
|--------|--------------|---------------------|-----|--------------------------------|--------------------------------|-------|
| 1      | $0.025 < z \leq 0.050$ | 7338                | 4.0 | 8.77                          | 9.35                          | $-18.26$ |
| 2      | $0.050 < z \leq 0.075$ | 13063               | 4.0 | 8.83                          | 9.60                          | $-18.78$ |
| 3      | $0.075 < z \leq 0.100$ | 12653               | 4.0 | 8.74                          | 9.78                          | $-19.21$ |
| 4      | $0.100 < z \leq 0.125$ | 9609                | 4.0 | 8.58                          | 9.96                          | $-19.62$ |
| 5      | $0.125 < z \leq 0.150$ | 6599                | 4.0 | 8.52                          | 10.08                         | $-19.98$ |
| 6      | $0.150 < z \leq 0.175$ | 3008                | 5.0 | 8.37                          | 10.20                         | $-20.34$ |
| 7      | $0.175 < z \leq 0.200$ | 1466                | 5.0 | 8.27                          | 10.33                         | $-20.63$ |
| 8      | $0.200 < z \leq 0.225$ | 953                 | 5.0 | 8.20                          | 10.40                         | $-20.83$ |
| 9      | $0.225 < z \leq 0.250$ | 304                 | 5.0 | 8.06                          | 10.47                         | $-21.02$ |

been observed in both samples. Moreover, in both samples, we observe a comparable increase in bulge masses and absolute magnitudes (cf. Figures 26 and 27 in the Appendix). Because these two observations are clearly independent of the aperture, this result suggests that the masses of the galaxies increase at higher redshift. Taken at face value, therefore, our observations are comparable to those made by Pilyugin & Thuan (2011), suggesting that the most massive galaxies formed first at high redshift.

However, we do not agree with the assumption made by Pilyugin & Thuan (2011) that the difference in abundance implies a decrease of SFR at high redshift. For example, in Figures 17 and 18 we observe an increase of late-type spirals and of younger stellar populations at higher redshift (cf. Figures 26 and 27 in the Appendix). These trends seem somewhat in contradiction with the other observations described above. Indeed, how can the bulges increase in mass at high redshifts while the number of late-type spirals and number of young stellar population also increase? The most plausible explanation is that, in fact, the SFR in both samples increases at higher redshift. Confirming this interpretation we show in Figure 19 for the SFG 1 and in Figure 20 for the SFG 2 the variation of SFH with redshift. For the SFG 1, all the galaxies at any redshift show a SFH consistent with constant SFR. There is consequently no evidence of a decrease of star formation with the redshift. Similarly, all the SFG 2 at any redshift show a starburst like nature (the peak at young age is higher than the peak at old age). This difference is consistent with their excess of nitrogen: at any redshift the SFG 2 are experiencing more intense bursts than the SFG 1 and consequently show more clearly the effect of starburst winds. However, and this is the most significant result yielded by STARLIGHT, in both samples we also observe a general increase of the SFRs with the redshift. This is fully consistent with downsizing, showing that the more massive galaxies formed first at higher redshifts.

Note that according to our analysis the downsizing phenomenon can be observed at almost any small increment of redshift. This was unexpected and somewhat surprising. Can we be wrong in our interpretation? That is, can this be, instead, the product of some sort of luminosity bias, the galaxies getting bigger and more massive because they are more luminous at high
Figure 18. Same as in Figure 17 for the nine SFG 2 subsamples.

Figure 19. SFH evolution with redshift in the SFG 1. The redshift of the galaxies increases from (1) to (9).
Figure 20. Same as Figure 19 for the SFG 2.

Figure 21. Illustration of the sequence of bursts model with starburst winds as main component. The star formation in the SFG 1 and SFG 2 can be reproduced by a sequence of bursts of star formation happening during their formation. Each burst causes the metallicity to increase and the ratio N/O to decrease. After $10^8$ yr the intermediate-mass stars formed during one burst begin to eject their nitrogen in the ISM, and the ratio N/O increases as the metallicity stay constant. The difference between the SFG 1 and SFG 2 is in the intensity of the bursts: in the SFG 2 more intense bursts, related to the formation of massive bulges, produce effective starburst winds, and the galaxies lose some of their oxygen. The number of intermediate stars being higher, the production of nitrogen is higher, and coupled with the lost in oxygen, a relative excess of nitrogen is observed for the same metallicity.
redshift? In our sample we do observe a decrease in the number of SFGs with the redshift (cf. Tables 7 and 8), which, taken at face value, may look as an argument in favor of a luminosity bias. However, this is inconsistent with the study of Strauss et al. (2002, p. 1), where the criteria for the SDSS spectroscopic survey are presented and discussed, and the authors conclude: “The uniformity and completeness of the galaxy sample make it ideal for studies of large-scale structure and the characteristics of the galaxy population in the local universe.” (We emphasized the completeness.)

In fact, the explanation for the “missing” galaxies is simple. Our sample is indeed biased, but in another way, which is that all the galaxies are SFGs, with an $S/N$ in line ratios $>3$. We verified that there are no missing galaxies in the SDSS survey at high redshift, simply they are not SFGs and do not satisfy our S/N criterion. In particular, we have found an important number of narrow line emission galaxies with weak or missing emission lines that complete the sample. All these galaxies have earlier morphological types than the SFGs and are found in clusters and groups (the majority are consistent with low-luminosity AGNs). In other words, the SDSS survey shows that the activity type of galaxies changes at higher redshift, including less and less SFGs, which is consistent with downsizing.

Within the hierarchical biased galaxy formation paradigm, assuming the starburst phenomenon is related with galaxy formation, the SFGs, which are all spirals, are typical of the field, which means they formed relatively recently from low-density fluctuations. At this level of density fluctuations the differences observed between the SFG 1 and SFG 2 must be related to very local variations, that is, on small scales of mass density, those leading to the formation of massive bulges. The downsizing phenomenon emphasizes that the redshift is really cosmological in nature. Rather than a variation of distance, it really describes a variation of state of the universe, namely here, its density.

5. CONCLUSION

In Coziol et al. (1997), it was reported that UV bright starburst galaxies are deficient in oxygen compared to normal late-type spirals. In Coziol et al. (1999), it was also reported that the
same sample of starburst galaxies shows a possible excess in nitrogen abundance. In the present study, using a much larger (122,751) and generally selected sample of SFGs (that is, the only restriction was that they do not show the presence of an AGN), we find exactly the same phenomena, suggesting that this is a common trait of SFGs and not a peculiar characteristic of starburst galaxies.

Our analysis of the SFH using STARLIGHT, in good agreement with Starburst99 models, suggests that the depletion in oxygen and the relative excess in nitrogen are most probably due to the effect of intense starburst winds (Heckman et al. 1990; Lehnert & Heckman 1996; Heckman 2003; Tremonti et al. 2004; Strickland & Heckman 2009) happening during a prolonged sequence of bursts of star formation. According to our analysis, all the SFGs form their stars through a sequence of bursts and what produces the chemical differences is a variation in intensity of the bursts. The SFGs experiencing the more intense bursts (with a median intensity above a particular threshold), or those that have experienced more intense bursts in the past, all show the effect of starburst winds: they are deficient in oxygen and relatively rich in nitrogen ($N/O$). We illustrate our model in Figure 21.

Contrary to expectation, however, we find no evidence that the efficiency of the starburst wind decreases with the mass of the galaxy. Instead, our data suggest the intensity of the bursts grows with the mass, and with it the depletion of oxygen and the excess

Figure 23. Confidence intervals associated with Figure 11 in Section 3.2: (a) morphologies; (b) stellar population ages; (c) bulge masses; and (d) total mass.
of nitrogen. To explain this observation, we propose that the abundance characteristics of these galaxies took shape during their formation process, when their gravitational wells were still forming, and consequently less massive and susceptible to decrease the efficiency of starburst winds. Consistent with this interpretation we have shown that the galaxies with an excess of nitrogen are the more massive, have bigger bulges and have an earlier morphological type than those without an excess. We have also found evidence consistent with downsizing, suggesting that the most massive galaxies formed first at higher redshift.

Considering the generality of our analysis we conclude that the formation process of the SFGs is an open process, the galaxies losing mass and energies to their environment.

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Figure 26. Confidence intervals associated with Figure 17 in Section 4: (a) metallicity; (b) nitrogen abundance; (c) morphologies; (d) stellar population ages; (e) bulge masses; and (f) total mass.

APPENDIX
RESULTS OF STATISTICAL TESTS

The statistical framework of the tests we used is based on a new parametric ANOVA model introduced by Hothorn et al. (2008) and developed for the R software\(^4\) by Herberich et al. (2010). The max-t test does the simultaneous pairwise comparisons of means under control of the familywise error rate, which is the probability of falsely rejecting the initial hypothesis (i.e., finding a significant difference among the means of any two groups in the data set even though there is actually no difference.

\(^{4}\) http://CRAN.R-project.org
present). The test takes into account possible heteroscedasticity and the unequal sizes of the groups.

We present the results of the tests under the form of simultaneous confidence intervals for all pairwise comparisons of group means. Confidence intervals including zero indicate no statistically significant differences. Confidence intervals near zero suggest some level of similarity. The farther from zero the more significant the differences. Note the smallness of some of the confidence intervals. This is due to the very large number of data used in each bin, which makes the tests extremely significant.

In Figure 22, we show the confidence intervals associated with Figure 8 (Section 3.1). The SFG 2 galaxies (a) have more mass; (b) have older stellar populations, (c) have more massive bulges, and (d) are more luminous in $B$ than the SFG 1.

In Figure 23, we present the confidence intervals associated with Figure 11 (Section 3.2), where we compare in the SFG 1 the variations of physical parameters in eight subsamples of metallicities: in (a) the morphologies are significantly different except in pairs of bins (1,2) and (6,3), the general trend is for an increase of metallicity in early-type galaxies; in (b) all the subsamples have different stellar population ages, the general trend being an increase of age with metallicity; in (c) the variation in bulge mass is less obvious (many bins show no difference) but the trend is clearly the mass increasing...
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