QUALITATIVE INTERPRETATION OF GALAXY SPECTRA

J. Sánchez Almeida\textsuperscript{1,2}, R. Terlevich\textsuperscript{3,4}, E. Terlevich\textsuperscript{3}, R. Cid Fernandes\textsuperscript{5}, and A. B. Morales-Luis\textsuperscript{1,2}

\textsuperscript{1} Instituto de Astrofísica de Canarias, E-38205 La Laguna, Tenerife, Spain; jos@iac.es, abml@iac.es  
\textsuperscript{2} Departamento de Astrofísica, Universidad de La Laguna, Tenerife, Spain  
\textsuperscript{3} Instituto Nacional de Astrofísica, Óptica y Electrónica, Tonantzintla, Puebla, Mexico; rjt@ast.cam.ac.uk, eterlevi@inaoep.mx  
\textsuperscript{4} Institute of Astronomy, University of Cambridge, Cambridge, UK  
\textsuperscript{5} Departamento de Física—CFM, Universidade Federal de Santa Catarina, P.O. Box 476, 88040-900 Florianópolis, SC, Brazil; cid@astro.ufsc.br

Received 2012 May 29; accepted 2012 July 16; published 2012 August 24

ABSTRACT

We describe a simple step-by-step guide to qualitative interpretation of galaxy spectra. Rather than an alternative to existing automated tools, it is put forward as an instrument for quick-look analysis and for gaining physical insight when interpreting the outputs provided by automated tools. Though the recipe is for general application, it was developed for understanding the nature of the Automatic Spectroscopic K-means-based (ASK) template spectra. They resulted from the classification of all the galaxy spectra in the Sloan Digital Sky Survey data release 7, thus being a comprehensive representation of the galaxy spectra in the local universe. Using the recipe, we give a description of the properties of the gas and the stars that characterize the ASK classes, from those corresponding to passively evolving galaxies, to H\textsc{ii} galaxies undergoing a galaxy-wide starburst. The qualitative analysis is found to be in excellent agreement with quantitative analyses of the same spectra. We compare the mean ages of the stellar populations with those inferred using the code \textsc{starlight}. We also examine the estimated gas-phase metallicity with the metallicities obtained using electron-temperature-based methods. A number of byproducts follow from the analysis. There is a tight correlation between the age of the stellar population and the metallicity of the gas, which is stronger than the correlations between galaxy mass and stellar age, and galaxy mass and gas metallicity. The galaxy spectra are known to follow a one-dimensional sequence, and we identify the luminosity-weighted mean stellar age as the affine parameter that describes the sequence. All ASK classes happen to have a significant fraction of old stars, although spectrum-wise they are outshined by the youngest populations. Old stars are metal-rich or metal-poor depending on whether they reside in passive galaxies or in star-forming galaxies.

Key words: atlases – galaxies: evolution – galaxies: general – methods: data analysis

Online-only material: color figure

1. INTRODUCTION

There are several automated tools for inferring the properties of the stellar populations contributing to the integrated galaxy spectra. The list includes \textsc{moped} (Panter et al. 2004), \textsc{starlight} (Cid Fernandes et al. 2005), \textsc{steckmap} (Ocvirk et al. 2006), \textsc{vespa} (Tojeiro et al. 2007), or \textsc{ulyss} (Koleva et al. 2009), as well as the use of line indices like the Lick indices (Worthey et al. 1994). Similarly, there are semiautomatic procedures to deduce the properties of the gas (e.g., Shaw & Dufour 1995; Johnson et al. 2006; Luridiana et al. 2012), including the so-called strong-line ratio methods (e.g., Pagel et al. 1979; Díaz & Pérez-Montero 2000; Denicolo et al. 2002; Shi et al. 2005). These tools are (and will be) fundamental for understanding the galaxy formation and evolution, but the blind use of the codes yields results that are quite unsatisfactory from a physical standpoint. One obtains a precise quantitative description of the stellar populations contributing to the integrated spectra, but ignores the reason why the code has chosen them rather than other potential alternatives. The educated eye of an astronomer is often far more telling from a physical point of view. Unfortunately, the know-how of qualitatively interpreting a spectrum is learned after a long experience of working in the field. The information on which particular spectral feature informs of which particular physical property is scattered among a large number of technical publications, which is difficult to identify and to deal with for a newcomer. This paper aims at providing a step-by-step guide to qualitative interpretation of galaxy spectra. Moreover, it will be compared with up-to-date numerical techniques to show that both qualitative and quantitative results are in excellent agreement.

The work was originally planned as a mere academic exercise to understand the nature of the classes resulting from the k-means classification of all the galaxy spectra in the Sloan Digital Sky Survey data release 7 (SDSS-DR7; Sánchez Almeida et al. 2010). We wanted to translate the spectral shapes into physical units like stellar ages and metallicities, so that this information can be used to tailor class-based searches (e.g., Aguerri et al. 2012), or when interpreting spectra (e.g., Sánchez-Janssen et al. 2012). However, the exercise is of interest beyond the original scope. The simple decision tree we use is suitable to characterize any galaxy spectrum. We know of its generality because it allows us to separate and characterize the 28 Automated Spectroscopic K-means-based (ASK) classes (Sánchez Almeida et al. 2010), which, by construction, are proxies that condense the properties of the some one-million SDSS spectra (Stoughton et al. 2002; Abazajian et al. 2009). The ASK class characterization represents a significant part of the paper, which are discussed in detail as an illustration of the procedure. As we stress above, our qualitative analysis may have several other applications, e.g., (1) to gain physical insight when interpreting quantitative star formation histories (SFHs) derived from modern automated tools, (2) for quick-look galaxy classification (not only in the local universe, but also at moderate-high redshifts, since the Hubble expansion shifts the UV–visible spectrum to the near IR), (3) for interpreting noisy spectra where...
eyeball inspection is often better than detailed inversion, (4) as reference for identifying unusual galaxies, or (5) for educational purposes to develop physical intuition.

The paper is organized as follows. Section 2 introduces the ASK spectral classification of galaxy spectra whose templates serve as reference point. Section 3 lists and discusses spectral features commonly used when interpreting galaxy spectra. They are employed to setup the recipe introduced in Section 3.2, which is abridged in a schematic shown in Figure 11. The recipe (or algorithm) is used in Section 4 to disclose the physical properties of all the ASK classes. The results of such qualitative analysis are compared with state-of-the-art quantitative analyses in Sections 5 and 6—Section 5 deals with the comparison of stellar components, whereas Section 6 refers to the gas components. Section 7 discusses several additional properties of the ASK templates, whereas Section 8 summarizes the proposed qualitative analysis.

2. ASK CLASSIFICATION

Sánchez Almeida et al. (2010) classified all the galaxies with spectra in SDSS-DR7 into only 28 ASK classes. The original SDSS covers one-fourth of the sky and contains the spectra of all the galaxies above an apparent magnitude threshold (SDSS; $r < 17.8$). Therefore, the same one-million SDSS spectra can be regarded as representative of the galaxies of the local universe, and so do the ASK classes inferred from them. The ASK classification is detailed in Sánchez Almeida et al. (2010), with additional properties of the classes discussed elsewhere (Sánchez Almeida et al. 2011; Ascasibar & Sánchez Almeida 2011; Aguerri et al. 2012). For the sake of comprehensiveness, however, we summarize here the main properties. All galaxies with redshift smaller than 0.25 were transformed to a common rest-frame wavelength scale, and then re-normalized to the integrated flux in the SDSS g-filter. These two are the only manipulations the spectra underwent before classification. We wanted the classification to be driven only by the shape of the visible spectrum (from 400 to 770 nm), and these two corrections remove obvious undesired dependencies of the observed spectra on redshift and galaxy apparent magnitude. We deliberately avoided correcting for other effects requiring modeling and assumptions (e.g., dust extinction, seeing, or aperture effects). The employed classification algorithm, k-means, is a robust workhorse that allows the simultaneous classification of the full data set (∼12 GB). It is commonly employed in data mining, machine learning, and artificial intelligence (e.g., Everitt 1995; Bishop 2006), and it guarantees that similar rest-frame spectra belong to the same class. Most galaxies (99%) were assigned to only 17 major classes, with 11 additional minor classes including the remaining 1%. It is unclear whether the ASK classes represent genuine clusters in the 1637 dimensional classification space, or if they slice a continuous distribution—probably the two kinds of classes are present (see Sánchez Almeida et al. 2010; Ascasibar & Sánchez Almeida 2011).

All the galaxies in a class have very similar spectra, which are also similar to the class template spectrum formed as the average of all the spectra of the galaxies in the class. These template spectra are the ones analyzed in the paper. The averaging is slightly different from the one in Sánchez Almeida et al. (2010), and the novelty allows us to reach the near UV of the spectrum. The SDSS spectrograph detects from 3800 Å to 9200 Å (e.g., Stoughton et al. 2002), however, the templates cover from 3000 Å to 9200 Å. The UV extension is recovered because the classified galaxies have redshifts up to 0.25, which moves the rest-frame $\lambda > 3000$ within the observed range. Rather than averaging the spectral range common to all galaxies, the new templates consider the full range of available rest-frame wavelengths. Given a wavelength bin, it includes the spectra of all the galaxies in the class that have been observed at that particular rest-frame wavelength. Consequently, the template spectra (i.e., the average spectra) include wavelengths down to 3000 Å. The templates thus obtained vary smoothly and continuously. They are labeled according to the $u-g$ color, from the reddest, ASK 0, to the bluest, ASK 27. The use of numbers to label the classes does not implicitly assumes the spectra to follow a one-dimensional family. The numbers only name the classes. The sorting (and, so, the naming) would have been slightly different using other bandpasses to define colors. In general, however, the smaller the ASK class number the redder the spectrum. The ASK classification of all galaxies with spectra in SDSS-DR7 is publicly available, templates included.6 Wavelengths of SDSS spectra (and of ASK templates) are vacuum wavelengths. However, all the spectra shown in this paper are transformed to air wavelengths according to the equations by Ciddor (1996). The SDSS spectra used for classification, and hence the templates shown along the paper, are given as flux per unit wavelength.

3. RECIPE FOR QUALITATIVE INTERPRETATION OF GALAXY SPECTRA

Galaxies have composite spectra. They integrate contributions from different stars of different stellar populations, from H ii regions, from active galactic nuclei (AGNs), as well as from other possible components (e.g., hydrogen ionized by old high-temperature stars, or by the intergalactic UV background; Cid Fernandes et al. 2004, 2010). Our qualitative analysis builds on this fact and tries to separate each spectrum into a minimum number of components. We consider the (ionized) gas and the stars separately, that is to say, the emission and absorption lines separately. Each one of these two components is assumed to have one or two sub-components. The details on the characterization are summarized as a decision tree in Section 3.2. It is based on the analysis of a set of general spectral features, listed in the next sub-section.

3.1. Spectral Features to be Considered in a Qualitative Analysis

The main spectral features that can be considered are listed in the section, ordered from the more obvious to the subtle details. Each item names the particular feature, and then outlines its main properties and interest. The actual features are illustrated using the appropriate ASK templates.

1. The shape of the continuum and the presence or not of emission and absorption lines must be considered. The emission lines trace the ionized gas and its excitation mechanism. The absorption lines trace the stellar populations, their ages, and metallicities. The overall continuum shape is modulated by the gas, the stars, as well as by the presence of dust. Figure 1 shows the prototype red galaxy with passively evolving stellar populations (ASK 0). Although red, the continuum is rather flat from 6000 Å on. Spectra even redder must be shaped by dust extinction (see ASK 1 in Figure 1).

6 ftp://ask.galaxy@ftp.iac.es/, http://sdg.cab.inta-csic.es/ask/index.jsp in the Spanish Virtual Observatory.
2. The so-called 4000 Å break is produced by the absorption of metallic lines of a variety of elements in various states of ionization, including Ca ii H and K (λλ 3969 and 3934) and high-order lines of the Balmer series (He λ 3970, Hα λ 3889, Hγλ3835, . . .; see Hamilton 1985, and also Figure 2). The opacity suddenly increases for photons bluer than this wavelength, which produces an intensity drop. It is enhanced in old stellar populations (ASK 0), which tend to be metal-rich, but it is also present in younger galaxies (ASK 19 in Figure 2). The Balmer lines become deeper and broader with time from the starburst, with a characteristic timescale of the order of 1 Gyr (e.g., González Delgado et al. 1999).

3. The limit of the Balmer series and the blending of the high-order Balmer lines also produces a notable discontinuity of the spectrum blueward of 3650 Å. It is the Balmer break—see Figure 2. (Photons bluer than this limit ionize the excited hydrogen, thus H becomes an important source of continuum opacity.) It is present in young and old stellar populations, but it is more important in the young populations where H is a major constituent of the opacity (especially in the Balmer continuum beyond the discontinuity). The break amplitude and position is a proxy for the age of the stellar population (e.g., Aretxaga et al. 2001).

4. The Ca ii H and K lines (λλ 3969 and 3934, respectively) are typical of old metal-rich stars. Ca ii H is blended with He, which, as the rest of the Balmer series, appears in absorption in young stars (say, A stars). In case of mixed populations of old and young stars, the relative intensities of Ca ii H and Ca ii K (actually, of Ca ii K and Ca ii H+He) is a proxy for the relative importance of the young and old populations. When Ca ii K is larger than Ca ii H, then the old population dominates the spectrum (ASK 2 in Figure 3). As the young population becomes more important then Ca ii H becomes stronger than Ca ii K (ASK 9 in Figure 3). The relative growth reverts when the H II regions accompanying the young stellar populations produce enough He emission, which fills the Ca ii H+He absorption profile (ASK 14 in Figure 3).

5. The UV continuum flux is also an age indicator for very young stellar populations. It increases with decreasing age when the ages are only a few Myr—see Figure 4 and,
e.g., Mas-Hesse & Kunth (1999). A symptom of extreme youth is the Balmer continuum showing up in emission ($\lambda < 3650$ Å), which happens with ASK 25 in Figure 4.

6. The ratio between the fluxes of H$\beta$ and [O iii] 5007 indicates whether the ionization is powered by a strong AGN ([O iii] 5007 $> H\beta$—ASK 6) or by a LINER-like source ([O iii] 5007 $< H\beta$—ASK 5).

7 We use the term LINER-like to refer to real Low-ionization nuclear emission-line regions (Heckman 1980), or evolved stars in retired galaxies (Flores-Fajardo et al. 2011), or X-ray emitting gas (e.g., Yan & Blanton 2012), or any other source with an ionizing UV spectrum harder than that of newborn stars, but not as hard as in a Seyfert galaxy or a quasar. Shock-heated gas may also produce lines in this part of the diagram (e.g., Baldwin et al. 1981; Allen et al. 2008).

7 We use the term LINER-like to refer to real Low-ionization nuclear emission-line regions (Heckman 1980), or evolved stars in retired galaxies (Flores-Fajardo et al. 2011), or X-ray emitting gas (e.g., Yan & Blanton 2012), or any other source with an ionizing UV spectrum harder than that of newborn stars, but not as hard as in a Seyfert galaxy or a quasar. Shock-heated gas may also produce lines in this part of the diagram (e.g., Baldwin et al. 1981; Allen et al. 2008).

8. The presence of [O iii] 4363 is also an indicator of low metallicity. The line is used to compute electron temperatures in H II regions, and it weakens with increasing metallicity to disappear at around $12 + \log(O/H) \approx 8.2$ (e.g., McGaugh 1991).

9. TiO bands at approximately 7150 Å, 7600 Å, and 8500 Å are characteristic of M stars, and they appear in all ASK classes except for the bluest ones (ASK 25 in the plot). Note also the presence of the IR Ca ii triplet in the middle of the third TiO band ($\lambda\lambda 8498, 8542,\ and\ 8662$).

10. The IR Ca ii triplet at $\lambda\lambda 8498, 8542$, and 8662 is an indicator of metallicity and gravity. In stars, its equivalent width (EW) increases with increasing metallicity until $2/3$ of the solar metallicity (Diaz et al. 1989). Above this metallicity it depends only on gravity, with the EW increasing with decreasing gravity from dwarfs to supergiants (Diaz et al. 1989; Cenarro et al. 2002). The combined effect on galaxy spectra must be modeled, but the existence of a Ca ii absorption with significant strength is always a sign of high
The Astrophysical Journal, 756:163 (15pp), 2012 September 10

Sánchez Almeida et al.

Figure 8. Spectral region containing the spectral indices Hβ and Mg2 (Hβ index from 4848 to 4877 Å and Mg2 from 5154 to 5197 Å). Both indices combined allow us to set mean age and mean metallicity in galaxies with old stellar populations. The labels mark the Hβ line and the position of the three Mg i lines contributing to Mg2.

Figure 9. Na i D is partly produced by ISM absorption. It is larger for the class with larger dust extinction (cf., Figure 1).

metallicity and of the presence of giant stars. In contrast, absence of the triplet indicates low metallicity. We find it in all ASK spectra except for the bluest classes (see Figure 7). As we mention in Section 4, the lines are almost absent in ASK 20 and bluer classes.

11. The so-called Mg2 and Hβ Lick indices are in the same spectral region (Hβ from 4848 to 4877 Å, and Mg2 from 5154 to 5197 Å; see Figure 8), and they were designed (and are used) to determine simultaneously age and metallicity in galaxies with old stellar populations (Worthey et al. 1994). One can generally say that Hβ mostly depends on age, and to less extent on metallicity, and the opposite happens with Mg2 (e.g., Vazdekis et al. 1996; Jørgensen 1999). However, their quantitative application require modeling (e.g., they may depend on the relative abundance of the metals, rather than on a single global metallicity).

12. The interstellar medium (ISM) that reddens the spectra also produces absorption in the Na i D line (λλ5891,5896; e.g., Asari et al. 2007; Chen et al. 2010). Therefore, one would expect that the strength of the ISM Na i D line sorts galaxies according to extinction (Asari et al. 2007). The example in Figure 9 corresponds to the two spectra in Figure 1, where ASK 1 is known to present a substantial dust extinction. Its Na i D is stronger than that for the class without extinction, ASK 0, being the rest of the spectrum similar.

13. The mere presence of high excitation lines like [Ne v]λ3426, [Fe vii]λ6087, or [Fe x]λ6375, tells us that the galaxy hosts an AGN (e.g., Reunanen et al. 2003; Goulding & Alexander 2009; Rodríguez-Ardila et al. 2011). The example in Figure 10 shows spectra in the range of [Fe vii]λ6087, whose emission is clear in Seyferts (ASK 7 and 8), but is non-existing in starbursts (ASK 20) as well as in passively evolving red galaxies with LINER-like emission (ASK 0; see Section 4). [He ii]λ4686 is also indicative of AGNs, though it is sometimes found in star-forming galaxies (e.g., Schaerer et al. 1999; Shirazi & Brinchmann 2012).

3.2. Decision Tree for Qualitative Analysis of Galaxy Spectra

Considering the spectral features described in the previous section, we have setup a simple decision tree (a questionnaire) that leads to classification of a galaxy spectrum by replying to a few questions (Figure 11). Emission and absorption lines are analyzed separately, therefore, the natural outcome would be galaxy types with two components, one for the stars and other for the gas. One should begin the questionnaire from top to bottom to end up with the characteristics of both the gas and the stars.

The decision tree in Figure 11 is self-explanatory, although a few clarifications on the terminology are required. The symbol G stands for galaxy. Broad spectral lines means lines in excess of 2000 km s−1, and they separate Seyfert 1 and quasars from the other kinds of AGNs. Such broad lines are not illustrated in Section 3.1 since the ASK classes lack Seyfert 1 and quasars, which were excluded from the list of galaxy targets directly at the SDSS distribution (see Schneider et al. 2007). When we mention young, old, and a mixture of old-and-young stellar populations, we roughly refer to stellar ages < 107 yr (young), > 109 yr (old), and the intermediate range in between, 107–109 yr. When metal-poor gas is mentioned, we mean clearly sub-solar (say, less than 1/3 solar). BL Lac objects are also included to complete the questionnaire, so that it considers the possibility that neither emission nor absorption lines are present in the spectrum (Stein et al. 1976; Massaro et al. 2012). Several criteria in Figure 11 compare emission lines—such comparison refers to the fluxes of the lines.
4. QUALITATIVE ANALYSIS OF THE ASK CLASSES

One may think of this section as analogous to the section on individual objects, common in many papers, except that the targets are ASK templates representing objects too numerous to be described one by one. We use the criteria put forward in the previous section to determine the properties of all ASK classes individually. The thread of the argumentation follows the decision tree in Figure 11. A summary with the properties of all classes is also given in Table 1. At the end of the section, we define a stellar age index (SAI) that sorts the ASK classes according to their mean stellar age. Similarly, we define an index to sort the emission-line spectra by metallicity. Both are relative quantities, devised to compare our qualitative analysis with quantitative estimates of ages and metallicities.

ASK 0 has an absorption line spectrum with very weak emission lines (Figure 1). It is not a starburst since \([\text{N} \text{II}]\lambda6853 > \text{H} \alpha\), but \([\text{O} \text{III}]\lambda5007\) and \(\text{H} \beta\) are too weak for us to determine whether the excitation is Seyfert-like or LINER-like. Note, however, that the EW of \(\text{H} \alpha\) is very small (Figure 5), which according to Cid Fernandes et al. (2011) indicates that the ionization is produced by hot low-mass stars. The absorption line spectrum does not show the Balmer break (Figure 2) but the 4000 Å break is conspicuous; consequently, the absorption spectrum is produced by an old metal-rich stellar population.

ASK 1 also has an absorption line spectrum with weak emission lines (Figure 1). \([\text{N} \text{II}]\lambda6853 \simeq \text{H} \alpha\), and therefore it is not a starburst. \(\text{H} \beta\) is smaller than \([\text{O} \text{III}]\lambda5007\), which may naively indicate AGN excitation. However, the lines are so weak that the underlying \(\text{H} \beta\) absorption is important and, therefore the corrected \(\text{H} \beta\) emission is similar to that of \([\text{O} \text{III}]\lambda5007\). Consequently, the emission-line spectrum is probably in the LINER region of the BPT diagram. The absorption line spectrum is also very similar to ASK 0, which was assigned to an old metal-rich stellar population. The main difference with respect to ASK 0 is the continuum, which steepens redward of 6000 Å (Figure 1), and is a signature of dust reddening. Additional independent arguments also corroborate that ASK 1 owes much of its red colors to reddening. ASK 1 galaxies tend to have very elongated morphologies, a fact difficult to interpret unless they are edge-on disks (Sánchez Almeida et al. 2011), which are known to be significantly dust reddened with respect to their face-on counterparts (e.g., Giovanelli et al. 1994; Masters et al. 2010).
Table 1
Qualitative Physical Properties of the ASK Template Spectra

| ASK Class         | Emission (Gas) | Absorption (Stars) | Comment                          | SAF | GMFi | O/Hii (Gas) | Age (Gyr)iz | Z/Z⊙iz |
|-------------------|---------------|-------------------|----------------------------------|-----|------|------------|-------------|---------|
| 0 AGN or LINER-like | Old metal-rich | Hz EW ∼ 0.9 Å4 |                                | 0   | ···  | ···         | 11.2 ± 1.2  | 1.30 ± 0.34 |
| 1 LINER-like      | Old metal-rich | Dust reddened, edge on disksb |                          | 0   | ···  | ···         | 10.0 ± 1.4  | 0.91 ± 0.34 |
| 2 AGN or LINER-like | Old metal-rich | [S II]λ6966 emission |                          | 1   | ···  | ···         | 11.1 ± 1.2  | 1.31 ± 0.34 |
| 3 LINER-like      | Old metal-rich | Continuum blueer than ASK 0 and 2 |                          | 2   | ···  | ···         | 6.7 ± 1.2   | 1.57 ± 0.38 |
| 4 LINER-like?     | Old and young | Edge-on disksb |                          | 3   | ···  | ···         | 7.4 ± 1.5   | 0.69 ± 0.36 |
| 5 LINER-like?     | Old and young | Green valley galaxies4  |                          | 3   | ···  | ···         | 6.0 ± 1.4   | 1.21 ± 0.43 |
| 6 Seyfert 2       | Old and young | [Fe ii]λ6087 emission |                          | 3   | ···  | ···         | 5.3 ± 1.3   | 1.35 ± 0.44 |
| 7 Seyfert 2       | Old and young | Younger than 6, [Fe vτ]λ6087 emission |                          | 4   | ···  | ···         | 5.2 ± 1.2   | 1.23 ± 0.44 |
| 8 Seyfert 2       | Old and young | Younger than 7, [Fe vτ]λ6087 emission |                          | 5   | ···  | ···         | 2.30 ± 0.71 | 1.05 ± 0.44 |
| 9 LINER-like      | Old and young | Metal-rich starburst? |                          | 3   | ···  | ···         | 3.6 ± 1.2   | 1.01 ± 0.44 |
| 10 Metal-rich starburst | Old and young | LINER-like? |                          | 3   | −0.35 | ···         | 4.1 ± 1.3   | 0.61 ± 0.34 |
| 11 Metal-rich starburst | Old and young | LINER-like?, stars younger than 9 and 10 |                          | 4   | −0.36 | ···         | 4.8 ± 1.4   | 0.43 ± 0.24 |
| 12 Metal-rich starburst | Old and young | Starburst prototype, stars younger than 11 |                          | 6   | −0.43 | 8.46 ± 0.18 | 2.7 ± 1.1 | 0.68 ± 0.35 |
| 13 Metal-rich starburst | Old and young | Stars similar to 12 |                          | 6   | −0.46 | ···         | 2.30 ± 0.93 | 0.90 ± 0.41 |
| 14 Metal-rich starburst | Old and young | Starburst prototype, stars younger than 12 |                          | 7   | −0.46 | 8.50 ± 0.11 | 1.71 ± 0.92 | 0.60 ± 0.30 |
| 15 Metal-poor starburst | No absorption | H α G, youngest ASK |                          | ··· | −1.67 | 7.85 ± 0.05 | ···         | ···     |
| 16 Metal-poor starburst | Old and young | ··· |                           | 7   | −0.65 | 8.77 ± 0.10 | 1.18 ± 0.72 | 0.58 ± 0.30 |
| 17 Metal-poor starburst | Young | H α G, stars older than 15 |                          | 13  | −1.58 | 8.06 ± 0.02 | 0.0048 ± 0.0008 | 1.29 ± 0.43 |
| 18 Metal-poor starburst | Young | Stars younger than 16 |                          | 8   | −0.54 | 8.61 ± 0.04 | 0.090 ± 0.038 | 0.52 ± 0.24 |
| 19 Metal-poor starburst | Young | Stars as in 18 |                          | 8   | −0.75 | 8.72 ± 0.05 | 0.249 ± 0.077 | 0.51 ± 0.25 |
| 20 Metal-poor starburst | Young | H α G, stars younger than 18, older than 17 |                          | 13  | −1.42 | 8.19 ± 0.01 | 0.0045 ± 0.0007 | 0.60 ± 0.33 |
| 21 Metal-poor starburst | Young | H α G, like 20, gas slightly metal-poorer |                          | 13  | −1.45 | 8.07 ± 0.01 | 0.0073 ± 0.0019 | 0.72 ± 0.34 |
| 22 Metal-poor starburst | Young | Like 19, stars younger, gas metal-richer |                          | 8   | −0.93 | 8.59 ± 0.04 | 0.138 ± 0.057 | 0.39 ± 0.17 |
| 23 Metal-poor starburst | Young | Like 19 and 22, stars younger |                          | 9   | −0.79 | 8.60 ± 0.02 | 0.056 ± 0.031 | 0.45 ± 0.24 |
| 24 Metal-poor starburst | Young | Like 23, stars younger |                          | 10  | −1.07 | 8.48 ± 0.02 | 0.062 ± 0.035 | 0.44 ± 0.22 |
| 25 Metal-poor starburst | Young | Like 20 and 21, stars older, gas metal-richer |                          | 12  | −1.27 | 8.29 ± 0.01 | 0.0083 ± 0.0018 | 0.72 ± 0.36 |
| 26 Metal-poor starburst | Young | Like 25, stars older, gas metal-richer |                          | 11  | −1.09 | 8.38 ± 0.02 | 0.0090 ± 0.0020 | 0.49 ± 0.28 |
| 27 Metal-poor starburst | Young | Like 25 |                          | 12  | −1.18 | 8.23 ± 0.02 | 0.0098 ± 0.0033 | 0.71 ± 0.34 |

Notes.

a From Sánchez Almeida et al. (2010), Table 2.

b Sánchez Almeida et al. (2011).

c Stellar age index, which orders stellar ages staring from the oldest (SAI = 0).

d Gas metallicity index (≡ log([N ii]λ6583/Hα)), which orders galaxies according to gas metallicity.

e12 + log(O/H) obtained via electron temperature and density. The error bars account for uncertainties inherited from errors in line fluxes.

f Luminosity-weighted average values using starlight. The error bars represent the dispersion among the SSP that contribute to the integrated light.

ASK 2 is very similar to ASK 0, as is our assignment—emission consistent with AGN or LINER-like excitation plus absorption corresponding to old metal-poor stars. The difference is in the continuum, which is somewhat redder in ASK 0, and also in the emission-line [S II]λ9069, which shows up in ASK 2 but not in ASK 0.

ASK 3 also shows an absorption line spectrum with weak emission. Emissions and absorptions are similar to those of ASK 0, therefore, the associated stellar population is old. As is the case with ASK 0, [O III]λ5007 and Hβ are too weak to decipher whether the emission is Seyfert or LINER-like. The difference with ASK 0, 1, and 2 is the continuum, which is bluest in ASK 3 (see Figure 12). Except for ASK 1, such variation reflects differences in the stellar populations, ASK 3 being the youngest. ASK 0, 2, and 3 were used to select a clean sample of red ellipticals by Aguerri et al. (2012).

ASK 4 spectrum has absorption lines and significant emission lines. The continuum is fairly red, similar to that of ASK 0 in Figure 1. Hz ∼ 2 × [N II]λ6853 and Hβ ≳ [O III]λ5007, therefore, according to the decision tree (Figure 11), it should be a LINER-like galaxy. However, it is in the region of the BPT diagram where AGN activity and star formation are difficult to disentangle (see Figure 13 in Sánchez Almeida et al. 2010).

Figure 12. Full spectral range for ASK 0, 1, 2, and 3 as indicated. The absorption features are similar but the continua become redder as the ASK number increases. This change is due to the aging of the stellar populations, except for ASK 1, which reflects enhanced extinction.

Figure 13. Absorption line spectrum shows both the Balmer break and the 4000 Å break, which correspond to a mixture of old and young stellar populations. The region around the break is shown in Figure 13.
ASK 5 has absorption and emission lines. The continuum is significantly bluer than that for ASK 4. Hα ≃ 2 × [N ii]λ6853 and Hβ ≳ [O iii]λ5007, therefore, according to the decision tree (Figure 11), it should be a LINER-like galaxy (with the caveat issued for ASK 4 still applying). The absorption line spectrum shows both the Balmer break at 3650 Å and the 4000 Å break, which correspond to a mixture of old and young stellar populations (like ASK 4 in Figure 13).

ASK 6 has intense emission lines on top of an absorption spectrum. Emission lines are broad (Figure 14), but not broad enough to be a Seyfert 1 galaxy (larger than 2000 km s⁻¹). It appears in the Seyfert region of the BPT diagram, therefore it is a Seyfert 2. [Fe v]λ6087 and [Ne v]λ3426 show up in emission confirming the AGN nature of the emission. It shows the Balmer break at 3650 Å and the 4000 Å break, which correspond to a mixture of old and young stellar populations. The breaks are extremely similar to that of ASK 4 in Figure 13.

ASK 7 is similar to ASK 6. The emission lines are broad (Figure 14), and it is also classified as Seyfert 2 according to the decision tree. [Fe v]λ6087 is detected, confirming the AGN nature of the emission (Figure 10). The absorption spectrum has a clear 4000 Å break, and the Balmer break is present but less pronounced than in the case of ASK 6 because the Balmer continuum rises blueward of the Balmer break. The absorption spectrum is also produced by a mixture of old and young stars, but probably younger than for ASK 6.

ASK 8 is similar to ASK 6 and 7, but the emission lines are even broader. It is also a Seyfert 2. [Fe v]λ6087 is detected, confirming the AGN nature of the emission (Figure 10). Following the trend from ASK 6 to ASK 7, the absorption spectrum shows the two breaks (Balmer and 4000 Å), but the Balmer continuum (blueward of 3650 Å) is more intense. The spectrum is also produced by a mixture of old and young stars, but probably younger than for ASK 7.

ASK 9 has absorption and emission lines. The lines are narrow, and Hα ≃ 2 × [N ii]λ6853 with Hβ ≳ [O iii]λ5007. According to the decision tree it has LINER-like emission, although it is close to being classified as a metal-rich starburst. The absorption spectrum presents well-defined Balmer and 4000 Å breaks, therefore, it is produced by a mixture of old and young stellar populations. The region of the breaks is similar to that of ASK 5.

ASK 10 has absorption and emission lines. The continuum is similar to that of ASK 9 except that it becomes redder beyond 7000 Å. Hα ≃ 2.5 × [N ii]λ6853 with Hβ ∼ 2 × [O iii]λ5007. According to the decision tree it corresponds to a metal-rich starburst, although it is close to the divide with LINER-like emission. The absorption spectrum is almost identical to the spectrum of ASK 9 in the region of the Balmer and 4000 Å breaks, and it is produced by a mixture of old and young stellar populations.

ASK 11 has both absorption and emission, but the emission lines are very intense. The red continuum is redder than in ASK 9 and 10, but the emission lines of ASK 11 are stronger. Hα ≃ 3 × [N ii]λ6853 with Hβ ∼ 2 × [O iii]λ5007. It corresponds to a metal-rich starburst, although it is close to the border to present LINER-like emission. The absorption spectrum is almost identical to the spectrum of ASK 9 in the region of the Balmer and 4000 Å breaks, except that the contribution of the Balmer lines is more important. It is produced by a mixture of old and young stellar populations, but the young population is more important than in the case of ASK 9 and 10.

ASK 12 spectrum has both absorption and emission lines. The continuum is bluer than that of ASK 10 and 11, but the emission lines are weaker. Hα ≃ 2.5 × [N ii]λ6853 with Hβ ∼ 1.5 × [O iii]λ5007. It represents a typical metal-rich starburst—it is right on the head of the seagull of the local BPT diagram corresponding to prototypical starbursts. The absorption line spectrum has the Balmer and 4000 Å breaks, but the 4000 Å break is less pronounced than that in ASK 10 and 11, and the Balmer series is more intense. The spectrum corresponds to mixed old and young stellar populations, but the young population is more important than in the case of ASK 9, 10, and 11.

ASK 13 spectrum has both absorption and emission lines. The continuum is bluer than that of ASK 11 and 12, but the emission lines are weaker. Hα ≃ 3 × [N ii]λ6853 with Hβ ∼ 2 × [O iii]λ5007. It is a starburst. The absorption line spectrum has the Balmer and 4000 Å breaks, and they are almost identical to
those for ASK 12. The spectrum corresponds to mixed old and young stellar populations similar to ASK 12.

ASK 14 spectrum has both absorption and emission lines. The continuum is bluer than that of ASK 12 and 13, and the emission lines more pronounced. \( \text{H\alpha} \gtrsim 3 \times [\text{N\textsc{i}}]_{\lambda6583} \) with \( \text{H\beta} \sim 1.5 \times [\text{O\textsc{iii}}]_{\lambda5007} \). It corresponds to a typical metal-rich starburst. The absorption line spectrum has the Balmer and 4000 Å breaks, but the 4000 Å break is barely noticeable. The spectrum corresponds to mixed old and young stellar populations, but the young population is more important than in the case of ASK 12 and 13.

ASK 15 is a pure emission-line spectrum. The EW of \( \text{H\beta} \) is of the order 200 Å, therefore, according the decision tree, it is an \( \text{H\textsc{ii}} \) galaxy. \( \text{H\alpha} \gg [\text{N\textsc{ii}}]_{\lambda6583} \) with \( \text{H\beta} \ll [\text{O\textsc{iii}}]_{\lambda5007} \). which corresponds to a low-metallicity starburst. The spectrum shows neither the Balmer break nor the 4000 Å break (even more extreme than ASK 17 in Figure 15). There are no metallic lines, and even the Balmer series shows no trace of absorption. This spectrum corresponds to the youngest stellar populations of the ASK series. ASK 15 has only 68 members (Sánchez Almeida et al. 2010), most of which look like compact galaxies, like those described by Cardamone et al. (2009) and Amorín et al. (2010), but a few of them are \( \text{H\textsc{ii}} \) regions in resolved galaxies.

ASK 16 spectrum has both absorption and emission lines. The continuum is bluer than that of ASK 13 and 14 including the upturn at the UV. \( \text{H\alpha} \gg [\text{N\textsc{ii}}]_{\lambda6583} \) with \( \text{H\beta} \sim [\text{O\textsc{iii}}]_{\lambda5007} \), which corresponds to a metal-poor starburst. The absorption line spectrum does show the Balmer break, but the 4000 Å break is barely noticeable. Consequently, the absorption line spectrum corresponds to a young stellar population, with hints of an old component. The TiO bands are hardly noticeable.

ASK 17 spectrum has only emission lines. (One can barely note the absorption of some of the Balmer lines; see Figure 15). Since the EW of \( \text{H\beta} \approx 150 \text{ Å} \), according to the decision tree ASK 17 is an \( \text{H\textsc{ii}} \) galaxy. The continuum is as blue as that of ASK 15 and includes the UV upturn (Figure 15). \( \text{H\alpha} \gg [\text{N\textsc{ii}}]_{\lambda6583} \) with \( \text{H\beta} \ll [\text{O\textsc{iii}}]_{\lambda5007} \), which corresponds to a metal-poor starburst. Even though absorption lines are not obvious, the spectrum shows the Balmer break (see Figure 15).

These two features correspond to extremely young stellar populations (although not as young as those in ASK 15).

ASK 18 spectrum has absorption and strong emission lines. The continuum is similar to that of ASK 16 but the upturn of the UV continuum is more pronounced. The emission lines are also stronger than those of ASK 16. \( \text{H\alpha} \gg [\text{N\textsc{ii}}]_{\lambda6583} \) with \( \text{H\beta} \ll [\text{O\textsc{iii}}]_{\lambda5007} \), which corresponds to a metal-poor starburst. The absorption line spectrum does show the Balmer break, but it does not have a 4000 Å break (similar to ASK 22 in Figure 13). The absorption line spectrum corresponds to a young stellar population.

ASK 19 spectrum presents absorption and strong emission lines. The continuum is bluer than that of ASK 18 but the emission lines are weaker. \( \text{H\alpha} \gg [\text{N\textsc{ii}}]_{\lambda6583} \) with \( \text{H\beta} \ll [\text{O\textsc{iii}}]_{\lambda5007} \), which corresponds to a metal-poor starburst. The absorption line spectrum shows the Balmer break, but it does not have a 4000 Å break, and it is similar to ASK 18. It corresponds to a young stellar population.

ASK 20 spectrum is dominated by strong emission lines but it also shows weak absorptions in the Balmer lines. The weak continuum is as blue as that of ASK 15, 17 or 19, and includes an UV upturn. We identify ASK 20 as an \( \text{H\textsc{ii}} \) galaxy. \( \text{H\alpha} \gg [\text{N\textsc{ii}}]_{\lambda6583} \) with \( \text{H\beta} \ll [\text{O\textsc{iii}}]_{\lambda5007} \), which corresponds to a metal-poor starburst. The absorption line spectrum shows the Balmer break, but it does not have a 4000 Å break. It also contains metallic lines (Ca II H and K). The absorption line spectrum corresponds to a young stellar population. Stars are older than those in ASK 17, but younger than those in ASK 19. The TiO bands are absent, and the IR Ca triplet is almost gone with a hint of showing up in emission.

ASK 21 is very similar to ASK 20, except that the lines are somewhat weaker. Probably the gas-phase metallicity is a bit higher in ASK 21 as judged from the ratio between \( \text{H\alpha} \) and \( [\text{N\textsc{ii}}]_{\lambda6583} \). In any case, the starburst is metal-poor.

ASK 22 spectrum presents absorption and strong emission lines. The continuum is similar to ASK 19, but bluer. The emission lines are somewhat stronger than those in ASK 19. \( \text{H\alpha} \gg [\text{N\textsc{ii}}]_{\lambda6583} \) with \( \text{H\beta} \ll [\text{O\textsc{iii}}]_{\lambda5007} \), which corresponds to a metal-poor starburst. The gas metallicity is a bit higher in ASK 19, as judged from the ratio between \( \text{H\alpha} \) and \( [\text{N\textsc{ii}}]_{\lambda6583} \). The absorption line spectrum shows the Balmer break, but it does not have a 4000 Å break, and it is similar to ASK 19. The absorption line spectrum corresponds to a young stellar population, probably younger than that in ASK 19.

ASK 23 spectrum is very similar to that of ASK 22 and ASK 19, except for having larger emission lines. The continuum is also a bit bluer. It corresponds to a metal-poor starburst with a young stellar population, presumably younger than that for ASK 19 and 22.

ASK 24 has a spectrum similar to ASK 23 (and ASK 22 and 19), with stronger emission lines. The continuum is bluer than in ASK 23. As judged from the ratio between \( \text{H\alpha} \) and \( [\text{N\textsc{ii}}]_{\lambda6583} \), the gas metallicity of ASK 23 is higher.

ASK 25 spectrum is similar to ASK 20 and 21, with the continuum a bit redder, and the lines weaker. As judged from the ratio between \( \text{H\alpha} \) and \( [\text{N\textsc{ii}}]_{\lambda6583} \), the gas metallicity of ASK 20 and 21 are smaller. The Balmer continuum shows up in emission (Figure 15).

ASK 26 spectrum is similar to ASK 25, with the continuum a bit redder, and the lines weaker. As judged from the ratio...
between Hα and [N II]λ6853, the gas metallicity of ASK 25 is smaller.

ASK 27 spectrum is very similar to that of ASK 25.

In order to carry out the comparison of this qualitative analysis with the quantitative analysis in Section 5, we define a stellar age index that sorts the ASK classes according to the age of their stellar populations. The SAI is defined as follows. Based on the absorption lines in the region containing the UV breaks and the UV continuum, we order the ASK classes according to their relative stellar ages. For instance, having stronger broader absorption lines of the same species with the same excitation potential, one can determine the electron temperature (e.g., [O III]λ4363 and [O III]λ5007). Similarly, lines of the same species with the same excitation potential but different collisional de-excitation rates, provide diagnostics for the electron density (e.g., [S II]λ6731 to [S II]λ6717). The average considers all the SDSS-DR7 SDSS-DR7.

The stellar metallicity grows slightly for older stellar populations (ASK 0) to the youngest one (ASK 0), with ASK 0 corresponding to the oldest reddest stellar populations (ASK 0) to the youngest bluest ones (ASK 0). ASK 0, 5, and 18 illustrate intermediate cases. Figure 17 is equivalent to Figure 16 except that, rather than mass, it shows the percentage of present light (at 4020 Å) produced by each one of the SSPs. Note how light is strongly biased toward young populations, as compared with mass, which is held by old populations. The dotted lines in the figure represent ± one standard deviation considering all the galaxies in SDSS-DR7 corresponding to a given ASK class. These are the histograms used to compute the luminosity-weighted averages and dispersions discussed in the next paragraph.

Figure 18(a) shows the relationship between the mean luminosity-weighted age as derived from starlight and the estimate of relative age carried out in Section 4 (SAI). The error bars give the rms fluctuations among the ages of the SSPs that contribute to each class. The correlation age–SAI is extremely good, implying that our quick qualitative estimate is consistent with the detailed up-to-date modeling. Moreover, the existence of an almost one-to-one correlation provides specific timescales to our qualitative dating. SAI between 0 and 2 correspond to a single old metal-rich population, with ages between 11.2 and 6.7 Gyr (see the SFH for ASK 0 in Figure 16). SAI between 3 and 7 has two stellar populations assigned, one old and one young (Table 1). They have mean ages between 7.4 Gyr and 1.2 Gyr. Finally, from SAI 8 onward, we qualitatively find young populations, and their mean starlight ages go from 250 Myr to 5 Myr.

Figure 18(b) displays the mean stellar metallicity corresponding to each SAI. The metallicity is high (slightly super-solar) when SAI ⩽ 2, i.e., in the classes our qualitative analysis cataloged as having old stellar populations. In this case the scatter is fairly small (see the error bars in the figure), meaning that all their old stars are metal-rich. The scatter increases and the mean metallicity decreases for younger populations. We interpret this result as an increase of the number of stellar populations that contribute to the galaxy spectra, which is corroborated by the SFHs of ASK 5, 14, and 18 in Figure 16 (with SAI 3, 7, and 8, respectively). The stellar metallicity grows slightly for spectra corresponding to even younger stellar populations, and it becomes slightly sub-solar for the youngest ASK classes. The scatter remains large, also reflecting the significant number of stellar components in these galaxies.

6. QUANTITATIVE ANALYSES OF THE EMISSION-LINE SPECTRA

One of the most sophisticated techniques of analysis of ionized nebulae involves measuring emission-line fluxes of many atomic species to derive their relative abundances. Adding up all the ionization states of an element provides its abundance. This approach is the so-called direct method or temperature-based method. The fluxes depend on atomic parameters as well as on the physical conditions of the plasma (e.g., Pagel & Edmunds 1981; Osterbrock 1989; Shields 1990; Stańiska 2004). Once the atomic parameters are known (or assumed), one can use the observed lines to retrieve, simultaneously, the elemental abundances and the physical conditions of the nebula. For instance, using collisional excited lines of the same species having different excitation potentials, one can determine the electron temperature (e.g., [O III]λ4363 and [O III]λ5007). Similarly, lines of the same species with the same excitation potential but different collisional de-excitation rates, provide diagnostics for the electron density (e.g., [S II]λ6731 to [S II]λ6717).
Figure 16. Each row corresponds to a particular ASK class as indicated. First column: SFHs derived from the application of starlight to spectra of individual galaxies, which are then averaged according to their classes. The classes on display have been chosen so that they cover the full range of possibilities, from the oldest reddest stellar populations (ASK 0) to the youngest bluest ones (ASK 20). ASK 5, 14, and 18 represent intermediate cases. The SFHs are two-dimensional functions with the abscissae representing look-back time and the ordinates representing metallicity. The scale of gray goes from maximum to minimum. Second column: the solid lines show the average of the SFHs along the metallicity axes. The dotted lines correspond to \( \pm \) one standard deviation from the average considering all the galaxies included in a given ASK class. Third column: same as the second column except that the average of the SFHs is carried out along the time axes. The spectrum of each ASK class is also shown for reference in the fourth column.

We have applied this technique to determine the oxygen abundance characteristic of the emission lines of the ASK classes that are starbursts. The actual recipe is described by Pérez-Montero & Díaz (2003) and Hägele et al. (2008), and it has been widely used (e.g., Amorín et al. 2010, 2012). We refer to the original references for details on the technique and atomic parameters. Whenever possible, the electron temperature was inferred from [O iii]\(\lambda\)4363. This line weakens with increasing metallicity, therefore, it cannot be used with the classes of large metallicities (see item 8 in Section 3.1). The problem was bypassed in these cases using [S iii]\(\lambda\)6312 and [S iii]\(\lambda\)9069 to derive the sulfur electron temperature, which was then used for oxygen after scaling (Hägele et al. 2006). ASK classes 17, 20, 21, 24, 25, 26, and 27 have [O iii]\(\lambda\)4363 intense enough to determine electron temperatures. The line is not detectable in classes 12, 14, 16, 18, 19, and 23, however they show [S iii]\(\lambda\)6312, which we used for deriving electron temperatures. Finally, classes ASK 10, 11, and 13 do not allow us to measure either [O iii]\(\lambda\)4363 or [S iii]\(\lambda\)6312, and so we could not assign an oxygen abundance using the direct method. Classes 20, 21, 22, 24, 25, 26, and 27 allow us to determine electron temperatures from both [O iii]\(\lambda\)4363 and [S iii]\(\lambda\)6312. The oxygen abundances obtained using the two ways of estimating temperature agree within \(\pm0.02\) dex. All the abundances thus obtained are listed in Table 1.

As we explain in Section 4, the metallicity of the gaseous component of the template spectra was judged based on the ratio between [N ii]\(\lambda\)6583 and H\(\alpha\). This ratio is therefore our qualitative metallicity index (Table 1), which is compared with the direct oxygen abundance in Figure 19. The correlation is extremely good, at least from solar metallicity (\(\log(O/H) = 8.69 \pm 0.05\); Asplund et al. 2009) to one-tenth the solar value. The fluctuations of the actual data with respect to a linear fit are just 0.06 dex, which is significantly smaller than the same correlation obtained from individual galaxies—e.g., Pettini & Pagel (2004) claim 0.2 dex. From the very good correlation between oxygen abundance and [N ii]\(\lambda\)6583/H\(\alpha\), we conclude that the qualitative analysis of nebular metallicities
Figure 17. Percentage of light corresponding to each one of the SSPs (first column), and its projection in the age axis (second column), and in the metallicity axis (third column). Same as Figure 16, except that the mass of each component has been weighted by the corresponding present light-to-mass ratio. The ASK classes have been chosen to represent the full range of possibilities, and they are the same as those in Figure 16. See the caption of Figure 16 for further details.

is consistent with the quantitative estimate using the best techniques available.

7. ADDITIONAL RESULTS AND DISCUSSIONS

Figure 20(a) shows the index used to determine the gas metallicity, log\([\text{N} \text{II}]\)\(\lambda 6583/\text{H} \alpha\), versus the index used to characterize the age of the stellar populations, SAI. It is clear that the two indices are correlated, indicating that the templates with the lowest oxygen content also have the youngest stellar populations. This is explicitly shown in Figure 20(b), which presents the same kind of relationship but using quantitative determinations of ages and gas-phase metallicities. (The two last points deviating from the linear relationship will be ignored since the trend they represent is not present in Figure 20(a), and they have particularly weak \([\text{O} \text{III}]\)\(\lambda 4363\) lines, with the uncertainties that this entails—see item 8 in Section 3.1.) The correlation is similar to that found by Fernandes et al. (2003). The physical origin of the relationship is unclear. It may be a side effect of the galaxy mass (a phenomenon often referred to as downsizing; see, e.g., Neistein et al. 2006). First, the mass–metallicity relationship implies that low-mass galaxies are less metallic (e.g., Skillman et al. 1989). Second, the mass–age relationship (e.g., Heavens et al. 2004) implies that low-mass galaxies also have younger stellar populations. Finally, the bluest ASK classes contain more dwarf galaxies (Sánchez Almeida et al. 2010), therefore, they are less metallic and with younger stars, giving as a side effect the observed correlation. Even though this explanation is feasible, the relationship between gas metallicity and stellar age shown in Figure 20 is so clean that it looks fundamental rather than derived from the combined effect of two other relationships. This conjecture is supported by the scatter plots in Figure 21, that include the two variables involved in Figure 20(b) plus the galaxy mass. Assigning masses to the ASK templates is not without ambiguity, since the spectra of the individual galaxies were normalized before averaging (Section 2). However, we computed the mean and standard deviation among the masses of all the galaxies in each ASK class, and those are the masses assigned to the classes in Figures 21. One can see that the templates follow a mass–metallicity relationship (Figure 21(b)) and a mass–age relationship (Figure 21(a)), but both are less tight than the metallicity–age relationship in Figure 20(b), which seems to be the primary relationship. In short, the properties of the gas and the stars are not independent but tightly correlated in

8 Stellar masses derived from integrated magnitudes using color-dependent mass-to-light ratios from Bell & de Jong (2001).
real galaxies. Galaxy mass does not seem to be the only factor driving such correlation.

Galaxy spectra seem to follow a one-dimensional sequence, with a secondary branch for AGNs (Connolly et al. 1995; Yip et al. 2004; Vanderplas & Connolly 2009; Ascasibar & Sánchez Almeida 2011). In other words, an independent parameter (affine parameter) characterizes most properties of galaxy spectra, from the red passive ones to those actively forming stars. The actual nature of the affine parameter is unknown, but the results in this paper suggest it to be the mean age of the stellar population. The ASK templates can be naturally ordered by mean stellar age (or by SAI, in our parlance), and the order thus obtained turns out to be extremely similar to the one obtained using minimal spanning trees by Ascasibar & Sánchez Almeida (2011). The latter represents a non-trivial exercise to find the location of the templates in the 1637 dimensional space where the ASK classification was carried out (i.e., a space where each galaxy is a point and the 1637 coordinates represent the flux at particular wavelengths). They are organized in a one-dimensional sequence with the same order given by the luminosity-weighted mean stellar age. We take the agreement between the two orderings as a strong suggestion that stellar age is the affine parameter. Note that the emission-line spectrum is prominent in blue galaxies and so it plays a major role in shaping the galaxy spectra. The fact that the spectrum of a galaxy is (mostly) dictated by the age of the stellar population implies that the emission lines and the absorption lines are not independent. This is indeed the conclusion reached in the previous paragraph through a totally different argument.

We argued in Section 2 that the ASK classes are representative of all local galaxies since they condense the properties of some one-million galaxies of the local universe. Even though we endorse the statement, it must be clarified. ASK templates are representative of the most common galaxies, however, some important but uncommon galaxies are not included. In particular, the most massive galaxies that dominate the centers of galaxy clusters (brightest cluster galaxies and cD galaxies) are not properly described. These massive red galaxies have old stellar populations so they are classified as ASK 0 and ASK 2 (Aguerri et al. 2012). However, they represent a small fraction of all the galaxies in these classes, so that their contribution to the average (template) spectra of ASK 0 and 2 is negligible. The same may happen with other kinds of rare objects like BL Lac (e.g., Stein et al. 1976), objects with extreme star formation rates (e.g., Cardamone et al. 2009), extremely metal-poor galaxies (e.g., Morales-Luis et al. 2011), and others. The fact that some objects may escape the simplified schematic in Section 3.2 do not invalidate the analysis, but it is useful to indicate that these objects are unusual.

The comparison between Figures 16 and 17 evidences a fact that is well documented in the literature, but the results of which are still somewhat surprising. Most galaxies formed
a significant fraction of their stellar mass long ago when the universe was just a few Gyr old, even those forming stars today (e.g., Heavens et al. 2004; Asari et al. 2007; Dunlop 2011). This fact is obviously true for ASK classes representing passively evolving red galaxies (see ASK 0 in Figure 16), but it also holds true for young ASK classes—see the important contribution of old stellar populations to the ASK 20 SFH in Figure 16, even though its luminosity-weighted mean age is just 4.5 Myr (Table 1). When the mass contribution is transformed to light contribution (Figure 17), it becomes clear how newborn stars outshine the older populations, that are heavily underrepresented in the composite galaxy spectrum. If a galaxy happens to undergo a significant starburst, spectrum-wise it looks young.

There is a conspicuous difference between the old stellar populations present in passively evolving galaxies and in star-forming galaxies. The metallicity of the old stars is high in passive galaxies and very low in starbursts (compare the SFHs of ASK 0 and ASK 20 in the first column of Figure 16). The dominance of old metal-rich stellar populations in red galaxies is well known (e.g., Renzini 2006), as is the fact that the old stars in dwarf galaxies of the local group have extremely low metallicity (e.g., Miller et al. 2001; Monelli et al. 2010; Hidalgo et al. 2011).

8. CONCLUSIONS

As argued in Section 1, we have sophisticated computer codes for inferring the properties of the stellar populations contributing to the observed galaxy spectra. Similarly, tools are available for qualitative diagnostics of the physical properties of the galaxy gas. They have been developed by specialist groups, and then kindly offered to a much broader community. Technicities often complicate the interpretation of the results, therefore, there is a natural tendency to apply these sophisticated tools in black-box fashion, which turns out to be quite unsatisfactory from a physical standpoint. One obtains a detailed description of the stars and gas producing the observed galaxy spectra, but overlooks the reasons why the computer code has preferred them rather than other alternatives. We provide a simple step-by-step guide to qualitative interpretation of galaxy spectra. It is not precise and has not been planned as an alternative to the existing tools. However, it allows a quick-look that yields the main properties of the spectra in an intuitive fashion. This may be of interest in various applications, e.g., to provide physical insight when using sophisticated tools, or to interpret noisy spectra. Moreover, the results of the qualitative analysis agree with those inferred using up-to-date computer codes.

The step-by-step guide is described in Section 3.2, and it has been summarized as a simple questionnaire in Figure 11. Emission and absorption lines are analyzed separately, which give rise to a classification with one entry for the gas and another for the stars. (In real galaxies, however, the properties of gas and stars are tightly correlated; see Section 7.) The analysis has been systematically applied to the set of ASK template spectra that resulted from the classification of all galaxy spectra in SDSS-DR7 (see Section 2). Their physical properties are summarized in Table 1. With the caveats pointed out in Section 7, the ASK classes represent a comprehensive set of galaxy spectra, that go all the way from passively evolving red galaxies (e.g., ASK 0) to H II galaxies, dominated by massive newborn stars having no absorption lines (e.g., ASK 15). Since it works for this set, the analysis should work for most galaxies.

The qualitative analysis is found to be in excellent agreement with quantitative numerical codes. We show how the index for stellar age (SAI) follows an almost one-to-one correlation with the mean stellar age assigned by the code STARLIGHT (Figure 18). Similarly, we found how the proxy for gas metallicity is in good agreement with the (oxygen) metallicity inferred by applying the direct method to the emission lines of the ASK templates (Figure 19).

The ASK templates are freely available (see footnote 6) and, together with their physical properties listed in Table 1, they can be used as benchmarks so that any other galaxy spectrum can be analyzed by reference to them.

Thanks are due to C. Ramos Almeida and E. Pérez-Montero for discussions and help with references. This work has been funded by the Spanish MICIN project Estallidos, AYA 2010-21887-C04-04. E.T. and R.T. acknowledge also financial support by the Mexican Research Council (CONACYT), through grants CB-2005-01-49847, 2007-01-84746, and 2008-103365-F. We are members of the Consolidor-Ingenio 2010 Program, grant MICINN CSD2006-00070: First Science with GTC. Funding for the SDSS and SDSS-II has been provided by the Alfred P. Sloan Foundation, the Participating Institutions, the National Science Foundation, the U.S. Department of Energy, the National Aeronautics and Space Administration, the Japanese Monbukagakusho, the Max Planck Society, and the Higher Education Funding Council for England. The SDSS is managed by the Astrophysical Research Consortium for the Participating Institutions (for details, see the SDSS Web site at http://www.sdss.org/). The STARLIGHT project is supported by the Brazilian agencies CNPq, CAPES, and FAPESP and by the France–Brazil CAPES/Cofecub program.

Facility: Sloan (DR7, spectra)

REFERENCES

Abazajian, K. N., Adelman-McCarthy, J. K., Agüeros, M. A., et al. 2009, ApJS, 182, 543
Aguerri, J. A. L., Huertas-Company, M., Sánchez Almeida, J., & Muñoz-Tuñón, C. 2012, A&A, 540, A136
Allard, F., Hauschildt, P. H., & Schwenke, D. 2000, ApJ, 540, 1005
Allen, M. G., Groves, B. A., Dopita, M. A., Sutherland, R. S., & Kewley, L. J. 2008, ApJS, 178, 20

"Figure 21. (a) Scatter plot of the mass of the galaxies in each ASK class vs. the mean stellar age. The vertical error bars represent the standard deviation among all the individual galaxies in each class. The horizontal error bars are the same as in Figure 20(b). (b) Scatter plot of the mass of the galaxies in a class vs. the gas-phase metallicity. The error bars have the same meaning as in panel (a)."
