SYNTHEIC SPECTRA OF H BALMER AND He I ABSORPTION LINES. II. EVOLUTIONARY SYNTHESIS MODELS FOR STARBURST AND POSTSTARBURST GALAXIES

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ABSTRACT

We present evolutionary stellar population synthesis models to predict the spectrum of a single-metallicity stellar population, with a spectral sampling of 0.3 Å in five spectral regions between 3700 and 5000 Å. The models, which are optimized for galaxies with active star formation, synthesize the profiles of the hydrogen Balmer series (Hβ, Hγ, Hδ, Hγ, H9, H10, H11, H12, and H13) and the neutral helium absorption lines (He I λ4922, He I λ4471, He I λ4388, He I λ4144, He I λ4121, He I λ4026, He I λ4009, and He I λ3819) for a burst with an age ranging from 10^6 to 10^9 yr, and different assumptions about the stellar initial mass function (IMF). Continuous star formation models lasting for 1 Gyr are also presented. The input stellar library includes non-LTE absorption profiles for stars hotter than 25,000 K and LTE profiles for lower temperatures. The temperature and gravity coverage is 4000 K ≤ T eff ≤ 50,000 K and 0.0 ≤ log g ≤ 5.0, respectively. The metallicity is solar.

It is found that the Balmer and He I line profiles are sensitive to the age, except during the first 4 Myr of the evolution, when the equivalent widths of these lines are constant. At these early stages of the evolution, the profiles of the lines are also sensitive to the IMF. However, strong H Balmer and He I lines are predicted even when the low-mass cutoff of the IMF is as high as 10 M☉. The equivalent widths of the Balmer lines range from 2 to 16 Å and those of the He I lines from 0.2 to 1.2 Å. During the nebular phase (cluster younger than about 10 Myr), Hβ ranges from 2 to 5 Å and He I λ4471 ranges between 0.5 and 1.2 Å. The strength of the lines is maximum when the cluster is a few hundred (for the Balmer lines) and a few tens (for the He I lines) of Myr old. In the continuous star formation scenario, the strength of the Balmer and He I lines increases monotonically with time until 500 and 100 Myr, respectively. However, the lines are weaker than in the burst models owing to the dilution of the Balmer and He I lines by the contribution from very massive stars.

The high spectral resolution of the profiles is useful to reproduce the absorption wings observed in regions of recent star formation and to estimate the effect of the underlying absorption on the nebular emission lines. The strength of the nebular emission Balmer and He I lines compared with the stellar absorption components indicates that H0 and the higher order terms of the Balmer series and He I are dominated by the stellar absorption component if an instantaneous burst is older than ≈ 5 Myr. Some of the He I lines (e.g., He I λ3819 and He I λ4922) are more favorable than others (e.g., He I λ4471) for the detection of stellar features in the presence of nebular emission. We estimate that the correction to the He I λ4471 nebular emission line due to the stellar absorption is between 5% and 25%, if the nebular emission has equivalent width between 10 and 2.5 Å (corresponding to a burst age between 1 and 3 Myr).

The models can be used to date starburst and poststarburst galaxies until 1 Gyr. They have been tested on data for clusters in the LMC, the super-star cluster B in the starburst galaxy NGC 1569, the nucleus of the dwarf elliptical NGC 205 and a luminous “E + A” galaxy. The full data set is available for retrieval at our websites or on request from the authors.

Subject headings: galaxies: evolution — galaxies: fundamental parameters — galaxies: starburst — galaxies: stellar content — line: profiles

1. INTRODUCTION

Starburst galaxies are characterized by a nebular emission-line spectrum at optical and an absorption-line spectrum at ultraviolet wavelengths. This dichotomy arises because starbursts are powered by massive stars (M ≥ 10 M☉). These stars emit photons with energies of a few tens of eV that are absorbed and reemitted in their stellar winds, producing ultraviolet resonance transitions and, thus, an ultraviolet absorption-line spectrum. However, most of the ionizing photons emitted by the stars can travel tens of parsecs or more before they are absorbed by the surrounding interstellar gas. Then, this ionized gas emits a nebular emission-line spectrum, mainly at optical and near-infrared wavelengths. However, around the Balmer jump the spectra can show absorption features formed in the photospheres of massive stars.

The radiative properties of starburst galaxies are determined by their massive stellar content. O, B, and A stars can...
dominate the optical continuum emission of starburst galaxies. The spectra of the early-type stars are characterized by strong hydrogen Balmer and neutral helium absorption lines and only very weak metallic lines (Walborn & Fitzpatrick 1990). However, the detection of these stellar features at optical wavelengths in the spectra of starburst galaxies is difficult because H and He I absorption features are coincident with the nebular emission lines that mask the absorption features. Even so, the higher order terms of the Balmer series and some of the He I lines are detected in absorption in many starburst galaxies (Storchi-Bergmann, Kinney, & Challis 1995; González-Delgado et al. 1995), in Seyfert 2 galaxies with their ultraviolet and optical continuum dominated by a nuclear starburst (Shields & Filippenko 1990; González-Delgado et al. 1998; Cid Fernandes, Storchi-Bergmann, & Schmitt 1998), or even in the spectra of giant H II regions (e.g., NGC 604; Terlevich et al. 1996). These features can be seen in absorption because the strength of the Balmer series in emission decreases rapidly with decreasing wavelength, whereas the equivalent width of the stellar absorption lines is constant or increases with wavelength. Thus, the net effect is that H α, H β, and H γ are mainly seen in emission, but the higher order terms of the series are seen in absorption. Very often, H α, H β, H γ, and H δ show absorption wings superposed on the nebular emission. A similar effect occurs for the He I lines. The strongest nebular emission occurs in the He I λ5876 and He I λ6678 lines, whereas the stellar absorption features are very weak. Meanwhile, the equivalent width of the nebular emission of He I λ4471 or He I λ4026 (≤6 Å; Izotov, Thuan, & Lipovetsky 1997) is similar to or even smaller than that of the stellar absorption lines. Thus, they can be easily detected in absorption.

Models of the H Balmer series and He I lines of a stellar population in a starburst galaxy can be used to predict the evolutionary state of a starburst, the effect of the initial mass function (IMF), and corrections to the nebular He and H I emission lines. Accurate measurements of the nebular emission lines are needed to estimate the amount of internal interstellar reddening, star formation rate, excitation parameter, and chemical abundances (in particular in the determination of the primordial helium abundance) in starburst galaxies. All these estimations are affected by the underlying H and He I stellar absorption. The internal interstellar reddening is derived using the Balmer decrement. The emission-line ratios (Hα/Hβ, Hγ/Hβ, Hδ/Hβ, …) are clearly affected by the stellar absorption. They are not affected equally because nebular emission decreases with wavelength. Reddening and underlying absorption affect line ratios such as [O II] λ3727+[O III] λ5007/Hβ and [O III] λ5007/Hβ that are used to estimate chemical abundances and the excitation parameter in starburst galaxies. The strength of the collisionally excited emission lines with respect to H β can be used to estimate the evolutionary state of starburst galaxies (García-Vargas, Bressan, & Díaz 1995; García-Vargas et al. 1997; González Delgado et al. 1999); higher line ratios are derived if H β is not corrected for the stellar absorption. The underlying stellar absorption in the He I lines leads to an underestimate of the He abundance in starburst galaxies and potentially of the determination of the primordial helium abundance. However, high-resolution spectra are needed to isolate the absorption lines from the nebular emission.

On the other hand, the strength of the higher order lines of the Balmer series and some of the He I lines (e.g., He I λ4026 and He I λ3819), which are likely to be detected in absorption in starburst galaxies, can be used to obtain information about the age and IMF of their stellar population. It has been suggested that starburst galaxies have a deficit of intermediate- and low-mass stars (Rieke et al. 1980; Viallefond & Thuan 1983; Augarde & Lequeux 1985; Scalo 1990). However, the evidence in favor of this top-heavy IMF in starburst galaxies is ambiguous (Satyapal et al. 1995, 1997). It should be expected that the strength of the Balmer absorption lines depends on the low-mass cutoff because these lines are stronger in A stars. Thus, if the mass of the starburst is distributed following a top-heavy IMF, we expect that the H Balmer lines are weaker than for the population with a nontruncated Salpeter IMF.

H Balmer and He I lines of a stellar population can be predicted using the evolutionary synthesis technique, a powerful tool to derive the properties of a stellar population taking as a free parameter the star formation history of the starburst (age, IMF, and star formation rate). This technique has been used previously to derive the strength of the Balmer and He I absorption lines of star-forming regions. Diaz (1988) used the synthetic profiles of H α, H β, H γ, and H δ computed by Kurucz (1979). She followed the evolution of the stellar cluster up to 40 Myr and found that the profiles are rather insensitive to the age and IMF. Olofsson (1995) computed the equivalent widths of the hydrogen (H α, H β, H γ, H δ, and Ly z) and He I (λ4026, λ4387, λ4471, and λ4921) lines of a single-burst star-forming regions at three different metallicities (Z = 0.001, 0.008, and 0.020) and followed the evolution up to 15 Myr. He used the synthetic models of Kurucz (1993) and Auer & Mihalas (1972) at a resolution of 5 Å. He found that the equivalent width of the Balmer lines increases during the course of the evolution, while He I decreases monotonically. The strength of these lines is very sensitive to the IMF and insensitive to the metallicity. He suggested that Balmer lines are prominent even if the low-mass cutoff is as high as 10 M⊙. Cananzi, Augarde, & Lequeux (1994) predict the Balmer lines (H β, H γ, and H δ) using stellar spectra of O to G type observed at a spectral resolution of 2 Å (Cananzi, Augarde, & Lequeux 1993). They conclude that the equivalent widths of the lines are more sensitive to the low-mass than to the high-mass cutoff of the IMF.

The results seem contradictory: it is not yet clear if the IMF parameters have an effect on the strength of the H Balmer and He I lines. On the other hand, none of the previous studies made predictions for the strength of the higher order Balmer series lines (H8–H13) that are least affected by the emission and the most useful to obtain information on the evolutionary state of the starburst. Owing to the coincidence of the nebular emission and absorption lines in the observed spectra of starbursts, models that compute the profiles of these lines at high spectral resolution are required to predict the underlying absorption through the analysis of the absorption wings. To achieve this goal, we have built a stellar library of synthetic spectra with a sampling of 0.3 Å, effective temperature from 50,000 to 4000 K, and gravity in the range 0 ≤ log g ≤ 5.0 (González Delgado & Leitherer 1999, hereafter Paper I). The profiles are computed using a set of programs developed by Hubeny and collaborators (Hubeny 1988; Hubeny & Lanz 1995a, 1995b; Hubeny, Lanz, & Jeffery 1995) in three stages. For T eff ≥ 25,000 K, the code TLUSTY is used...
to compute non-LTE stellar atmosphere models. These models together with Kurucz (1993) LTE stellar atmosphere models (for $T_{\text{eff}} \leq 25,000$ K) are used as input to SYNSPEC, the program that solves the radiative transfer equation. Finally, the synthetic spectrum is obtained after performing the rotational and instrumental convolution. This library has been included in our evolutionary synthesis code (Starburst99; Leitherer et al. 1999) to predict the strength of the Balmer and He I lines for a stellar population.

This paper is organized as follows: Section 2 describes the models, the assumptions, and computational techniques. Section 3 deals with the results and discusses the effects of the IMF parameters and metallicity on the strength of the lines. We compare the equivalent widths of the Balmer and He I absorption lines with the values predicted for the nebular recombination emission lines in §4. In §5, the models are compared with observations of stellar clusters of the Large Magellanic Clouds, the super–star clusters in the starburst galaxy NGC 1569, the nucleus of the dwarf elliptical galaxy NGC 205, and a luminous “E + A” galaxy. The summary and the conclusions are in §6.

2. DESCRIPTION OF THE MODELS

The stellar library of synthetic spectra that covers the main hydrogen Balmer and neutral He lines (Paper I) has been implemented in our evolutionary synthesis code Starburst99 (Leitherer et al. 1999). The synthesis is done in two steps. First, the code computes the population of stars in the cluster as a function of age and IMF; then the profiles of the lines are synthesized by adding the different contributions from stars.

Two limiting models of the star formation history are considered: an instantaneous burst and star formation proceeding continuously at a constant rate. In the instantaneous burst, all the stars are formed at the same time on the zero-age main sequence (ZAMS) and then evolve in the Hertzsprung-Russell diagram (HRD) until 1 Gyr. These models are normalized to a total mass of $10^6 M_\odot$. The star formation rate of the continuous model is $1 M_\odot \text{yr}^{-1}$; they extend to 1 Gyr.

The models are generated for different assumptions about the IMF, which is parameterized as a power law, $\Phi(m) = C m^{-\alpha}$, where the constant $C$ is determined by the total gas mass converted into stars. The reference model is a power law with exponent $\alpha = 2.35$ and with low-mass and high-mass cutoff masses of $M_{\text{low}} = 1 M_\odot$ and $M_{\text{up}} = 80 M_\odot$. For comparison, we have computed models with $\alpha = 3.3$ and $\alpha = 1.0$ between $M_{\text{low}} = 1 M_\odot$ and $M_{\text{up}} = 80 M_\odot$, and a truncated Salpeter ($\alpha = 2.35$) IMF between $M_{\text{low}} = 1 M_\odot$ and $M_{\text{up}} = 30 M_\odot$, $M_{\text{low}} = 5 M_\odot$ and $M_{\text{up}} = 80 M_\odot$, and $M_{\text{low}} = 10 M_\odot$ and $M_{\text{up}} = 80 M_\odot$.

The models are computed with the isochrone synthesis method. Thus, continuous isochrones are calculated by interpolating between the tracks in the HRD on a variable mass grid. The stars evolve from the ZAMS following the new set of evolutionary tracks of the Geneva group (Schaller et al. 1992; Schaerer et al. 1993a, 1993b; Charbonnel et al. 1993; Meynet et al. 1994), with standard mass-loss rate.

The time resolution of the models is 0.01 Myr; however, the profiles of the lines are given only at time steps during which significant changes occur. For every step, the luminosity, effective temperature, radius, and surface gravity are calculated for each star. Then a spectrum of our stellar library is assigned to each star. The corresponding synthetic spectrum is flux calibrated using the stellar atmosphere grid compiled by Lejeune, Buser, & Cuisinier (1997). This com-
pilation, which includes the 20 Å resolution Kurucz (1993) stellar atmospheres, is supplemented by Schmutz, Leitherer, & Gruenwald (1992) models for stars with expanding envelopes. The flux of the continuum is assigned to each normalized spectrum by fitting a first-order polynomial to the plane \((F_\lambda, \log \lambda)\), where \(F_\lambda\) is the distribution of the corresponding low-resolution stellar atmosphere model. The fit is done taking points of the continuum adjacent to the absorption lines \(H_\beta, H_\gamma, H_\delta,\) and \(He\ i \lambda 4471\) for the spectral ranges 4820–4950 Å, 4270–4430 Å, 3990–4150 Å, and 4420–4580 Å, respectively. To calibrate the stellar spectra between 3720 and 3920 we use the result of the fit in the wavelength range of \(H_\delta\) (if \(T_{\text{eff}} \geq 12,000\) K) or \(H_\beta\) (if \(T_{\text{eff}} \leq 12,000\) K) extrapolated to those wavelengths. The calibration was chosen to achieve consistency between the distribution of the continuum flux of our synthesized high-resolution spectra and the spectral energy distribution, which is also predicted by our code at a resolution of 20 (see Fig. 1). The nebular continuum has been added to the synthesized spectra. We have assumed that all the stellar far-UV photons below 912 Å are absorbed by gas and converted into continuous and line emission at longer wavelengths.

We have computed the synthesized profiles for two metallicities, \(Z = 0.02\) (\(Z_\odot\)) and \(Z = 0.001\) (1/20 \(Z_\odot\)). While the input stellar evolutionary tracks are different for these two metallicities, we use the same stellar library (generated assuming solar metallicity) because the profiles of the Balmer lines of individual stars do not change significantly with metallicity for \(T_{\text{eff}} \geq 7000\) K (see Paper I).

3. MODEL RESULTS

Figure 2 shows the synthetic spectra for a star cluster formed instantaneously 3, 50, and 500 Myr ago. The IMF is Salpeter with \(M_{\text{low}} = 1 M_\odot\) and \(M_{\text{up}} = 80 M_\odot\); the metallicity is solar. The general tendency is that the strength of the Balmer lines increases with the evolution until 500 Myr, and the \(He\ i\) lines until 30–40 Myr.

The equivalent widths of the Balmer (Tables 1 and 2) and \(He\ i\) (Tables 3 and 4) lines are measured in the windows indicated in the Figure 2. Two different measurements are made, one integrating the flux from the continuum set to unity and the other from a pseudocontinuum. This pseudocontinuum is found fitting a first-order polynomial (except for the spectral range 3720–3920 Å, for which we use a third-order fit) to the continuum windows defined in Table 3 of Paper I. The absolute values of the equivalent widths depend on the continuum level and on the width on the windows used to measure the strength of the lines. However, the relative behavior of the equivalent width with age of the star cluster is independent of the continuum and of the width of the windows. We plot the equivalent widths measured from the pseudocontinuum because these measurements are more representative of the equivalent widths we can measure in observed spectra.

First, we discuss the profiles and equivalent widths of \(H\) Balmer and \(He\ i\) lines for the reference model (Salpeter IMF, \(M_{\text{low}} = 1 M_\odot\), and \(M_{\text{up}} = 80 M_\odot\)) for an instantaneous burst and for continuous star formation. Then, the effect of the IMF parameters and finally the effect of the

![Fig. 2.—Synthetic spectra from 3700 to 5000 Å predicted for an instantaneous burst formed following a Salpeter IMF between \(M_{\text{low}} = 1 M_\odot\) and \(M_{\text{up}} = 80 M_\odot\) at ages 3, 50, and 500 Myr. The horizontal lines indicate the windows used for measuring the equivalent widths.](image-url)
metallicity are discussed. The full data set is available for retrieval at our websites or on request from the authors.¹

3.1. The Hydrogen Absorption Lines

Figure 3 shows the equivalent widths of the Balmer lines as a function of the age for an instantaneous burst. We plotted the equivalent width measured from the pseudocontinuum and integrating the flux in the windows of 60 Å for Hβ, Hγ, and Hδ, and 30 Å for H8, H9, and H10, respectively. All the Balmer lines have similar behavior; the equivalent widths are in the range 2–16 During the first 4 Myr, the equivalent width does not change, with Hβ, Hγ, and Hδ ~ 3 Å, which is very similar to the values predicted by Olofsson (1995) and very similar to the value estimated (~2 Å) for the Balmer absorption in giant H II regions (Shields & Searle 1978; McCall, Ribsky, & Shields 1985).

The equivalent width increases with the age of the burst until 500 Myr; then, it decreases. The maximum is at 500 Myr since the turnoff stellar population in the cluster are stars of type A2 V that have a lifetime of several hundreds of Myr. These stars have Teff ~ 9000 K, and at this the strength of the Balmer lines peaks (see, e.g., Fig. 2 in Paper I). The predicted value at 500 Myr (the equivalent width of Hβ ~ 11–12 Å) is, e.g., in agreement with the values measured in the super–star clusters of NGC 1275 (Brodie et al. 1998) and the values predicted by population synthesis models using stellar clusters (Bica & Alloin 1986a).

For continuous star formation, the strength of the lines increases with time until 500 Myr; then, the equivalent widths are constant (Fig. 4). The equivalent widths range from 3 to 10 Å. They are very similar to the burst models at the beginning of the evolution (about 3 Å for continuous

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¹ http://www.iaa.es/ae/e2.html and http://www.stsci.edu/science/starburst/; rosa@iaa.es.
star formation lasting for 4 Myr). However, the equivalent width increases less rapidly with time than in the burst model. The reason is the dilution of the Balmer lines by O stars, which have weaker Balmer lines than A stars and which are continuously forming in the cluster.

3.2. The Neutral He Absorption Lines

Figure 5 shows the equivalent width of some of the He I lines. He I λ4471 and He I λ4026 are the strongest lines; they have equivalent widths that range between 0.5 and 1.1 Å. He I λ4922, He I λ4388, and He I λ3819 are about a factor of 2 weaker than He I λ4471 and He I λ4026. This result is opposite to that found by Olofsson (1995). However, observations of individual Galactic B stars (Lennon, Dufton, & Fitzsimmons 1993) show that the lines He I λ4471 and He I λ4026 have both similar strength and are about a factor of 2 stronger than He I λ4922 and He I λ4388 (these two lines have also similar strength). We found the same result when we examined the spectral atlas of Walborn & Fitzpatrick (1990).

The equivalent width of the He I lines is almost constant for bursts younger than 4 Myr, with He I λ4471 and He I λ4026 being about 0.5 Å, and He I λ4922, He I λ4388, and He I λ3819 about 0.3 Å. After 4 Myr, the equivalent width increases with age (but not monotonically) until the burst age reaches 30–40 Myr owing to the contribution of early-type B stars that show the strongest He I absorption. This result is opposite to that found by Olofsson (1995). He followed the evolution of the starburst until 15 Myr, and he found that the maximum strength of the He I lines is at 2 Myr; no He I absorption is formed in his model bursts older than 10 Myr. Lennon et al. (1993) show that stars from O9 to B2 have similar strengths of the He I λ4471 and He I λ4026 lines; these are weaker in stars hotter than O9 and cooler than B2. By definition He I lines are not formed in the photosphere of stars cooler than B9. These observations are in agreement with the results found in our stellar grid (see Fig. 4 of Paper I) and explain why the equivalent width of these lines in the integrated light of a stellar cluster have their maximum values between 10 and 40 Myr, when the cluster is dominated by early B stars. He I absorption is not formed for bursts older than 100 Myr because the lifetime of B9 stars is about this age.

The equivalent width has some local maximum between 5 and 20 Myr. This is due to the presence of post–main-sequence stars with $T_{\text{eff}} \leq 8000$ K that contribute significantly to the integrated light of the cluster at these ages (Fig. 6). These are the blue loops of the red supergiant in the tracks. These stars do not produce He I lines but show many metal lines close to the He I lines (Fig. 7). These metal lines are in the spectral windows used to measure the equivalent width. They depress the continuum and contribute to the integrated profile making it broader and asymmetric (Fig. 8). A similar effect is also seen in the H Balmer lines. However, the contribution of these metallic lines to the equivalent width of the window where the Balmer lines are

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**Table 2**

| Age (Myr) | Hβ (Å) | Hγ (Å) | Hδ (Å) | Hδ (Å) | H9 (Å) | H10 (Å) |
|-----------|--------|--------|--------|--------|--------|---------|
| 0 ....... | 2.6    | 2.8    | 3.2    | 2.5    | 2.0    | 1.7     |
| 1 ....... | 2.6    | 2.8    | 3.1    | 2.4    | 2.0    | 1.7     |
| 2 ....... | 2.6    | 2.8    | 3.1    | 2.4    | 2.0    | 1.8     |
| 3 ....... | 2.6    | 2.7    | 3.1    | 2.4    | 2.0    | 1.8     |
| 4 ....... | 2.7    | 2.9    | 3.3    | 2.5    | 2.2    | 1.9     |
| 5 ....... | 3.2    | 3.0    | 3.7    | 2.9    | 2.6    | 2.2     |
| 6 ....... | 3.4    | 3.1    | 3.8    | 3.0    | 2.8    | 2.2     |
| 7 ....... | 3.6    | 3.3    | 4.1    | 3.2    | 3.0    | 2.4     |
| 8 ....... | 3.8    | 3.3    | 4.2    | 3.3    | 3.1    | 2.4     |
| 9 ....... | 3.8    | 3.4    | 4.3    | 3.4    | 3.2    | 2.5     |
| 10 ....... | 3.8    | 3.5    | 4.4    | 3.4    | 3.2    | 2.5     |
| 15 ....... | 4.1    | 3.7    | 4.8    | 3.7    | 3.5    | 2.8     |
| 20 ....... | 4.3    | 4.1    | 5.1    | 4.0    | 3.7    | 3.0     |
| 30 ....... | 4.6    | 4.4    | 5.6    | 4.3    | 4.1    | 3.3     |
| 40 ....... | 4.8    | 4.7    | 6.0    | 4.7    | 4.3    | 3.6     |
| 50 ....... | 5.0    | 5.1    | 6.3    | 4.9    | 4.5    | 3.8     |
| 60 ....... | 5.1    | 5.3    | 6.5    | 5.0    | 4.7    | 3.9     |
| 70 ....... | 5.1    | 5.5    | 6.6    | 5.2    | 4.8    | 4.0     |
| 80 ....... | 5.2    | 5.7    | 6.7    | 5.2    | 4.9    | 4.1     |
| 90 ....... | 5.4    | 5.9    | 6.9    | 5.3    | 4.9    | 4.1     |
| 100 ....... | 5.6    | 6.1    | 7.1    | 5.4    | 5.0    | 4.2     |
| 200 ....... | 6.5    | 6.6    | 7.9    | 6.3    | 5.7    | 4.7     |
| 300 ....... | 7.1    | 7.2    | 8.6    | 6.6    | 6.0    | 4.8     |
| 400 ....... | 7.5    | 7.6    | 9.2    | 7.0    | 6.4    | 5.1     |
| 500 ....... | 7.8    | 8.0    | 9.6    | 7.2    | 6.6    | 5.2     |
| 600 ....... | 8.0    | 8.2    | 10.0   | 7.4    | 6.8    | 5.3     |
| 700 ....... | 8.2    | 8.3    | 10.2   | 7.5    | 6.9    | 5.3     |
| 800 ....... | 8.2    | 8.4    | 10.3   | 7.6    | 7.0    | 5.4     |
| 900 ....... | 8.2    | 8.5    | 10.3   | 7.6    | 7.0    | 5.4     |
| 1000 ...... | 8.2    | 8.4    | 10.3   | 7.6    | 7.1    | 5.3     |

* The mass is distributed following a Salpeter IMF between a $M_{\text{low}} = 1 M_\odot$ and $M_{\text{up}} = 80 M_\odot$. 

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The mass is distributed following a Salpeter IMF between a $M_{\text{low}} = 1 M_\odot$ and $M_{\text{up}} = 80 M_\odot$. 

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measured is less than that to the windows of the He I lines because the Balmer lines are relatively stronger.

For continuous star formation (CSF), the equivalent width ranges between 0.5 and 0.9 Å for (He I \( \lambda 4471 \) and He I \( \lambda 4026 \)). The strength of these lines increases with time until \( \approx 100 \) Myr; then, the equivalent widths decrease with time (Fig. 9). At 40 Myr after the onset of the star formation, the equivalent widths of the lines (He I \( \lambda 4471 \) and He I \( \lambda 4026 \)) is 0.8 Å. They are weaker than in the instantaneous burst model of the same age. However, owing to the presence of B stars in the cluster, the He I lines are stronger in the continuous star formation scenario than in the instantaneous burst after 100 Myr.

### 3.3. The Hydrogen Balmer and He I Absorption Lines as a Function of the IMF Parameters

We study the influence of the slope of the IMF on the profile and equivalent width of the hydrogen Balmer and He I lines in a single stellar population. The models computed have IMF slopes \( \alpha = 1.0 \) and \( \alpha = 3.3 \), low-mass cutoffs \( M_{\text{low}} = 5 \, M_\odot \) and \( M_{\text{low}} = 10 \, M_\odot \), and high-mass cutoffs \( M_{\text{up}} = 30 \, M_\odot \) with respect to the reference model (\( \alpha = 2.35 \), \( M_{\text{low}} = 1 \, M_\odot \), and \( M_{\text{up}} = 80 \, M_\odot \)).

Figure 10 shows the change of the profiles of H\( \delta \) and He I (\( \lambda 4026 \), \( \lambda 4009 \), and \( \lambda 4143 \)) with the slope of the IMF for a 2 Myr old burst. Clusters formed with an IMF flatter than Salpeter produce hydrogen Balmer lines weaker than in the reference model because more massive stars are formed in the cluster. At 2 Myr, these stars dilute the strength of the Balmer and He I lines since these lines are weaker in O than in B stars. However, after 4 Myr the relative number of massive stars still on the main sequence with respect to B and A stars is very low. At that epoch, the profiles and equivalent widths of these lines are almost the same as those of the reference model (Fig. 11). He I lines are also weaker than in the reference model if the cluster is younger than 4 Myr. These lines are slightly stronger if the cluster is between 20 and 100 Myr old (Fig. 12). During the post-starburst phase, the integrated light is dominated by B stars, and for a flatter IMF, the relative number of B stars with respect to A stars is slightly higher than in the reference model. This effect, however, is very small. The opposite result is found if the IMF is steeper than the Salpeter IMF. In this case the Balmer and He I lines are stronger than in the reference model if the burst is younger than 4 Myr. Between 20 and 100 Myr, He I lines are weaker than in the Salpeter model because fewer B stars contribute to the integrated light of the cluster. However, at these ages the change of the strength of these lines (Fig. 12) is less important than at ages younger than 4 Myr, when the equivalent width can change by almost a factor of 2 (Figs. 11 and 12).

Figure 13 shows the change of H\( \delta \) and He I (\( \lambda 4026 \), \( \lambda 4009 \), and \( \lambda 4143 \)) with \( M_{\text{low}} \) and \( M_{\text{up}} \) for a 2 Myr old burst. The H\( \delta \) and He I lines are stronger if \( M_{\text{up}} = 30 \, M_\odot \) than in the reference model, but they are very similar to those predicted

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### Table 3

| Age (Myr) | \( \lambda 4922 \) (Å) | \( \lambda 4471 \) (Å) | \( \lambda 4388 \) (Å) | \( \lambda 4026 \) (Å) | \( \lambda 3819 \) (Å) |
|-----------|-----------------|-----------------|-----------------|-----------------|-----------------|
| 0         | 0.25            | 0.47            | 0.19            | 0.52            | 0.29            |
| 1         | 0.24            | 0.47            | 0.18            | 0.52            | 0.29            |
| 2         | 0.28            | 0.51            | 0.19            | 0.55            | 0.32            |
| 3         | 0.40            | 0.60            | 0.25            | 0.60            | 0.40            |
| 4         | 0.43            | 0.61            | 0.32            | 0.64            | 0.41            |
| 5         | 0.96            | 0.91            | 0.73            | 0.94            | 0.64            |
| 6         | 0.90            | 0.87            | 0.64            | 0.81            | 0.59            |
| 7         | 1.2             | 0.96            | 0.96            | 1.0             | 0.77            |
| 8         | 0.52            | 0.80            | 0.47            | 0.87            | 0.65            |
| 9         | 0.61            | 0.89            | 0.50            | 0.94            | 0.71            |
| 10        | 0.60            | 0.94            | 0.49            | 0.97            | 0.75            |
| 11        |                 | 0.94            | 0.43            | 1.0             | 0.73            |
| 12        | 0.49            | 0.94            | 0.40            | 1.0             | 0.74            |
| 13        |                 | 1.2             | 0.70            | 1.1             | 0.85            |
| 14        | 0.92            | 1.1             | 0.81            | 1.2             | 0.92            |
| 15        | 0.67            | 0.90            | 0.69            | 1.0             | 0.64            |
| 16        | 0.49            | 0.76            | 0.52            | 0.82            | 0.53            |
| 17        | 0.49            | 0.80            | 0.49            | 0.89            | 0.59            |
| 18        | 0.49            | 0.81            | 0.50            | 0.90            | 0.59            |
| 19        | 0.49            | 0.82            | 0.52            | 0.91            | 0.59            |
| 20        | 0.51            | 0.83            | 0.54            | 0.92            | 0.62            |
| 25        | 0.58            | 0.90            | 0.60            | 1.0             | 0.65            |
| 30        | 0.58            | 0.93            | 0.62            | 1.1             | 0.70            |
| 35        | 0.61            | 0.94            | 0.64            | 1.1             | 0.70            |
| 40        | 0.63            | 0.94            | 0.65            | 1.1             | 0.69            |
| 45        | 0.63            | 0.92            | 0.65            | 1.1             | 0.69            |
| 50        | 0.61            | 0.91            | 0.63            | 1.1             | 0.65            |
| 60        | 0.86            | 0.82            | 0.62            | 1.0             | 0.60            |
| 70        | 0.56            | 0.80            | 0.60            | 0.90            | 0.61            |
| 80        | 0.76            | 0.58            | 0.86            | 0.56            |                |
| 90        | 0.69            | 0.56            | 0.78            | 0.46            |                |
| 100       | 0.68            | 0.56            | 0.74            | 0.44            |                |
TABLE 4

Equivalent Width of He I (Å) for Continuous Star Formation at Solar Metallicity

| Age (Myr) | \( \lambda 4922 \) (Å) | \( \lambda 4471 \) (Å) | \( \lambda 4388 \) (Å) | \( \lambda 4026 \) (Å) | \( \lambda 3819 \) (Å) |
|-----------|-----------------|-----------------|-----------------|-----------------|-----------------|
| 0 .......... | 0.25            | 0.47            | 0.21            | 0.50            | 0.29            |
| 1.0 ....... | 0.25            | 0.46            | 0.21            | 0.50            | 0.29            |
| 2.0 ....... | 0.25            | 0.48            | 0.22            | 0.51            | 0.30            |
| 3.0 ....... | 0.29            | 0.52            | 0.24            | 0.53            | 0.32            |
| 4.0 ....... | 0.34            | 0.55            | 0.25            | 0.57            | 0.35            |
| 5.0 ....... | 0.44            | 0.59            | 0.32            | 0.61            | 0.38            |
| 6.0 ....... | 0.54            | 0.64            | 0.37            | 0.64            | 0.42            |
| 7.0 ....... | 0.60            | 0.68            | 0.43            | 0.68            | 0.45            |
| 8.0 ....... | 0.64            | 0.70            | 0.44            | 0.70            | 0.45            |
| 9.0 ....... | 0.64            | 0.71            | 0.44            | 0.70            | 0.47            |
| 10 .......... | 0.64            | 0.73            | 0.45            | 0.72            | 0.48            |
| 15 .......... | 0.65            | 0.76            | 0.47            | 0.76            | 0.54            |
| 20 .......... | 0.63            | 0.77            | 0.48            | 0.78            | 0.53            |
| 30 .......... | 0.63            | 0.79            | 0.52            | 0.80            | 0.56            |
| 40 .......... | 0.62            | 0.82            | 0.54            | 0.81            | 0.58            |
| 50 .......... | 0.62            | 0.85            | 0.58            | 0.83            | 0.59            |
| 60 .......... | 0.62            | 0.90            | 0.59            | 0.83            | 0.59            |
| 70 .......... | 0.62            | 0.90            | 0.59            | 0.84            | 0.58            |
| 80 .......... | 0.62            | 0.91            | 0.59            | 0.82            | 0.59            |
| 90 .......... | 0.61            | 0.90            | 0.60            | 0.82            | 0.57            |
| 100 .......... | 0.62            | 0.89            | 0.61            | 0.83            | 0.57            |
| 200 .......... | 0.62            | 0.75            | 0.57            | 0.82            | 0.53            |
| 300 .......... | 0.61            | 0.71            | 0.56            | 0.77            | 0.53            |
| 400 .......... | 0.60            | 0.69            | 0.54            | 0.71            | 0.47            |
| 500 .......... | 0.60            | 0.67            | 0.55            | 0.71            | 0.49            |
| 600 .......... | 0.61            | 0.67            | 0.56            | 0.74            | 0.48            |
| 700 .......... | 0.62            | 0.67            | 0.59            | 0.72            | 0.50            |
| 800 .......... | 0.63            | 0.70            | 0.60            | 0.72            | 0.49            |
| 900 .......... | 0.63            | 0.70            | 0.60            | 0.72            | 0.50            |
| 1000 ...... | 0.63            | 0.70            | 0.60            | 0.72            | 0.50            |

Fig. 3.—Equivalent widths of the Balmer lines measured in a window of 60 Å width for \( \text{H} \beta \), \( \text{H} \gamma \), and \( \text{H} \delta \) and 30 Å width for \( \text{H} 8 \), \( \text{H} 9 \), and \( \text{H} 10 \). The flux is integrated from the pseudocontinuum defined by fitting a first-order polynomial (except for the range 3720–3920 Å) to the continuum windows defined in Table 3 of Paper I.
by the reference model if $M_{\text{low}} = 5 \, M_\odot$. This result holds as long as the burst is younger than 5 Myr because the lifetime of stars with mass higher than $30 \, M_\odot$ is less than 5 Myr. Thus, if the cluster is younger than 5 Myr and if the mass is distributed following a standard Salpeter IMF, the integrated light should be dominated by stars more massive than $30 \, M_\odot$. These stars have Balmer and He I lines that are weaker than stars less massive than $30 \, M_\odot$. In this case, the Balmer and He I lines are diluted with respect to the truncated ($M_{\text{up}} = 30 \, M_\odot$) IMF. However, after 5 Myr, all the stars more massive than $30 \, M_\odot$ have evolved from the main sequence, and the integrated light shows Balmer and He I lines of the same strength.

If the cluster is formed following a truncated Salpeter IMF with $M_{\text{low}} = 5 \, M_\odot$, the integrated light shows the Balmer and He I lines at a similar strength as in a cluster formed following the standard Salpeter IMF. The lifetime of stars with mass of $5 \, M_\odot$ is about 100 Myr. Clusters formed

**Fig. 4.**—Same as Fig. 3 but for continuous star formation models.

**Fig. 5.**—Equivalent widths of the He I lines measured in a window of 14 Å width for He I $\lambda 4922$, $\lambda 4471$, and $\lambda 4388$, of 11 Å for He I $\lambda 4026$, and 7 Å for He I $\lambda 3819$. The flux is integrated from the pseudocontinuum defined fitting a first-order polynomial (except for the range 3720–3920 Å) to the continuum windows defined in Table 3 of Paper I.
Fig. 6.—Isochrone at 14 Myr (left) and 25 Myr (right) for a burst of $10^6 M_\odot$ formed following a Salpeter IMF between $M_{\text{low}} = 1 M_\odot$ and $M_{\text{up}} = 80 M_\odot$ at solar metallicity. The size of the circle is scaled by the product of the number of stars in each mass (effective temperature) interval and the luminosity.

If the IMF is steeper than the reference one or if the upper mass cutoff is much lower than $80 M_\odot$, fewer O stars are formed, and the Balmer and He I lines are stronger. If the IMF is flatter than Salpeter or if the low-mass cutoff is higher than $5 M_\odot$, more O stars are formed relative to B and A stars, and the lines are weaker. However, the ability of the Balmer and He I lines to constrain the IMF depends strongly on the resolution of the observations and on the

Fig. 7.—Synthetic spectra in the spectral range 4015–4040 Å normalized to the pseudocontinuum for stars with $T_{\text{eff}}$ equal to 20,000, 10,000, and 6000 K.
Fig. 8.—Profile of He I λ4026 for an instantaneous burst formed following a Salpeter IMF between $M_{\text{low}} = 1 M_\odot$ and $M_{\text{up}} = 80 M_\odot$ at ages 4, 14, and 25 Myr.

Spatial distribution of the stellar cluster with respect to the nebular emission because at ages younger than 5 Myr starbursts show very strong He I and Balmer emission lines that fill in the absorptions. A nearby starburst, which can be spatially resolved and where the core stellar cluster shines through a hole of nebular emission produced by the stellar winds, will show a spectrum with absorption wings around the Balmer emission and with the He I lines in absorption; NGC 604 is a good example of this (see Fig. 9 in Terlevich et al. 1996). In these cases, the He I lines that are fainter in emission (e.g., He I λ4026, λ4388, and λ4026) can be dominated by the stellar absorption. Thus, under these circumstances, the equivalent widths of these lines and the wing absorption profiles of the higher terms of the Balmer series can be used to constrain the IMF (R. M. González Delgado & E. Pérez 1999, in preparation). When these circumstances do not occur, the total integrated spectrum of a starburst will be dominated by the nebular emission while it is younger than 5 Myr (see also § 4), and the stellar lines will not be detected; therefore, any information about the star-

Fig. 9.—Same as Fig. 5 but for continuous star formation models (SFR = 1 $M_\odot$ yr$^{-1}$)
Fig. 10.—Synthetic profiles of a 2 Myr old instantaneous burst formed with a mass distributed between $M_{\text{low}} = 1 M_\odot$ and $M_{\text{up}} = 80 M_\odot$ at solar metallicity following a power-law IMF with index $\alpha = 2.35$ (full line), $\alpha = 1.0$ (dashed line), and $\alpha = 3.3$ (dotted line).

Fig. 11.—Equivalent width of H$\beta$ for an instantaneous burst at solar metallicity formed following different assumptions about the IMF parameters.

Fig. 12.—Same as Fig. 10 for the line He I $\lambda 4471$. 
burst will be obtained through the analysis of the emission lines.

3.4. The Effect of Metallicity

In Paper I we demonstrated that the strengths of the Balmer and He I lines in individual stars hotter than 7000 K do not depend on metallicity. However, the strength of these lines in the integrated light of a stellar cluster depends on metallicity owing to the metallicity-dependent stellar population. At low metallicity, a star of a given ZAMS mass is hotter and evolves more slowly in the HRD, explaining why the Balmer lines are weaker at \( Z = 0.001 \) than at solar metallicity (Fig. 14; Table 5). At any age younger than 500 Myr, main-sequence stars that dominate the luminosity of the cluster have higher effective temperature at \( Z = 0.001 \) than at solar metallicity. After 500 Myr, stars hotter than 9000 K are still in the main sequence at \( Z = 0.001 \) metallicity. Therefore, the equivalent width of the Balmer lines

![Graph showing the effect of metallicity on the equivalent width of the Balmer lines](image1)

**Fig. 13.**—Synthetic profile of a 2 Myr old instantaneous burst formed with a mass following a Salpeter IMF at solar metallicity with \( M_{\text{low}} = 1 \, M_\odot \) and \( M_{\text{up}} = 80 \, M_\odot \) (continuous line), \( M_{\text{low}} = 5 \, M_\odot \) and \( M_{\text{up}} = 80 \, M_\odot \) (dotted line), and \( M_{\text{low}} = 1 \, M_\odot \) and \( M_{\text{up}} = 30 \, M_\odot \) (dashed line).

**Fig. 14.**—Equivalent width of the Balmer lines for an instantaneous burst at \( Z = 0.02 \) (continuous line) and \( Z = 0.001 \) (dashed line) metallicity formed following a standard Salpeter IMF.
TABLE 5

Equivalent Width of the Balmer Series (Å) for an Instantaneous Burst at a Metallicity Z = 0.001

| Age (Myr) | Hβ (Å) | Hγ (Å) | Hδ (Å) | H8 (Å) | H9 (Å) | H10 (Å) |
|-----------|--------|--------|--------|--------|--------|---------|
| 0         | 2.2    | 2.5    | 2.8    | 2.2    | 1.8    | 1.4     |
| 1         | 2.2    | 2.4    | 2.8    | 2.1    | 1.7    | 1.4     |
| 2         | 2.1    | 2.3    | 2.5    | 2.0    | 1.6    | 1.35    |
| 3         | 2.2    | 2.3    | 2.5    | 2.0    | 1.6    | 1.37    |
| 4         | 4.2    | 3.8    | 4.3    | 3.9    | 3.7    | 3.0     |
| 5         | 3.5    | 3.4    | 3.9    | 3.1    | 2.9    | 2.5     |
| 6         | 3.3    | 3.3    | 3.9    | 3.0    | 2.7    | 2.4     |
| 7         | 3.4    | 3.3    | 4.2    | 3.1    | 2.7    | 2.5     |
| 8         | 3.6    | 3.5    | 4.4    | 3.3    | 2.8    | 2.7     |
| 9         | 3.7    | 3.7    | 4.5    | 3.4    | 2.9    | 2.7     |
| 10        | 3.8    | 3.6    | 4.6    | 3.4    | 3.0    | 2.8     |
| 15        | 4.6    | 4.5    | 5.5    | 4.2    | 3.8    | 3.4     |
| 20        | 5.2    | 4.8    | 6.2    | 4.8    | 4.3    | 3.7     |
| 25        | 5.6    | 5.1    | 6.5    | 5.2    | 5.1    | 4.0     |
| 30        | 5.8    | 5.6    | 6.7    | 5.3    | 4.8    | 4.1     |
| 40        | 6.4    | 6.2    | 7.3    | 5.9    | 5.4    | 4.4     |
| 50        | 6.9    | 6.8    | 8.0    | 6.3    | 5.8    | 4.8     |
| 60        | 7.3    | 7.3    | 8.4    | 6.7    | 6.3    | 5.0     |
| 70        | 7.5    | 7.5    | 8.7    | 7.0    | 6.5    | 5.2     |
| 80        | 7.8    | 7.9    | 9.2    | 7.4    | 6.9    | 5.5     |
| 90        | 8.0    | 8.1    | 9.5    | 7.6    | 7.1    | 5.7     |
| 100       | 8.3    | 8.5    | 9.9    | 7.8    | 7.3    | 5.8     |
| 200       | 9.5    | 10.0   | 11.8   | 9.1    | 8.5    | 6.6     |
| 300       | 9.6    | 10.0   | 12.3   | 9.2    | 8.7    | 6.5     |
| 400       | 9.7    | 10.2   | 12.6   | 9.3    | 9.0    | 6.4     |
| 500       | 9.7    | 10.4   | 12.9   | 9.6    | 9.2    | 6.7     |
| 600       | 9.9    | 10.5   | 13.3   | 9.7    | 9.5    | 6.8     |
| 700       | 10.2   | 11.0   | 13.7   | 10.1   | 9.8    | 7.0     |
| 800       | 10.4   | 11.3   | 14.2   | 10.2   | 10.0   | 7.1     |
| 900       | 10.6   | 11.5   | 14.5   | 10.5   | 10.3   | 7.4     |
| 1000      | 10.8   | 11.8   | 15.1   | 10.8   | 10.5   | 7.3     |

Fig. 15.—Same as Fig. 13 but for He i λ4471
The luminosity of the He I recombination lines have been calculated from the ratio He I λ4471/Hβ and the theoretical ratio He I λ4026/He I λ4471 (0.474), He I λ4922/He I λ4471 (0.274), and He I λ3819/He I λ4471 (0.264).

### Table 6

| Age (Myr) | λ4471 (Å) | λ4388 (Å) | λ4026 (Å) | λ3819 (Å) |
|-----------|-----------|-----------|-----------|-----------|
| 0         | 0.43      | 0.18      | 0.47      | 0.25      |
| 1         | 0.42      | 0.17      | 0.46      | 0.25      |
| 2         | 0.38      | 0.16      | 0.43      | 0.22      |
| 3         | 0.43      | 0.17      | 0.44      | 0.24      |
| 4         | 0.36      | 0.35      | 0.38      | 0.19      |
| 5         | 0.60      | 0.36      | 0.40      | 0.40      |
| 6         | 0.68      | 0.38      | 0.70      | 0.40      |
| 7         | 0.79      | 0.41      | 0.74      | 0.49      |
| 8         | 0.81      | 0.43      | 0.80      | 0.54      |
| 9         | 0.82      | 0.45      | 0.84      | 0.55      |
| 10        | 0.83      | 0.50      | 0.88      | 0.57      |
| 20        | 0.88      | 0.54      | 1.0       | 0.62      |
| 25        | 0.93      | 0.57      | 1.0       | 0.63      |
| 30        | 1.0       | 0.62      | 1.0       | 0.68      |
| 40        | 1.0       | 0.68      | 1.0       | 0.67      |
| 50        | 0.97      | 0.70      | 1.0       | 0.67      |
| 60        | 0.93      | 0.67      | 1.0       | 0.64      |
| 70        | 0.91      | 0.69      | 1.0       | 0.62      |
| 80        | 0.89      | 0.70      | 0.95      | 0.61      |
| 90        | 0.86      | 0.70      | 0.93      | 0.57      |
| 100       | 0.85      | 0.67      | 0.90      | 0.57      |
| 200       | 0.75      | 0.70      | 0.85      | 0.49      |
| 300       | 0.72      | 0.75      | 0.80      | 0.38      |
| 400       | 0.65      | 0.72      | 0.74      | 0.39      |
| 500       | 0.60      | 0.70      | 0.63      | 0.37      |
| 600       | 0.61      | 0.69      | 0.64      | 0.45      |
| 700       | 0.59      | 0.73      | 0.60      | 0.47      |
| 800       | 0.57      | 0.70      | 0.60      | 0.47      |
| 900       | 0.59      | 0.73      | 0.58      | 0.51      |
| 1000      | 0.59      | 0.81      | 0.57      | 0.52      |

The equivalent width of the H Balmer and He I absorption lines in this section is calculated from the relationship between the intensity of the line and the number of Lyman continuum photons and the theoretical ratios (assumining case B; Osterbrock 1989) Hγ/Hβ (0.469), Hδ/Hβ (0.259), and H8/Hβ (0.105). The luminosity of the He I recombination lines have been calculated from the ratio He I λ4471/Hβ and the theoretical ratio He I λ4026/He I λ4471 (0.474), He I λ4922/He I λ4471 (0.274), and He I λ3819/He I λ4471 (0.264).

We estimate the ratio He I λ4471/Hβ using the photoionization code CLOUDY (Ferland 1997). The models are computed assuming that the gas is ionization bounded and is spherically distributed around the ionizing cluster with a constant density of 100 cm⁻³. The chemical composition of the gas is solar, and the ionizing photon luminosity is fixed to the values predicted by the evolutionary synthesis models. We take as the radiation field the spectral energy distribution predicted by Starburst99 (Leitherer et al. 1999).

Models are computed for an instantaneous burst with age between 0 and 20 Myr and continuous star formation lasting up to 100 Myr. Tables 7 and 8 show the ratio He I λ4471/Hβ and the equivalent width of the He I and H Balmer lines for burst and continuous star formation, respectively.

The ratio He I λ4471/Hβ decreases with the age of the instantaneous burst, and drops to zero for a burst older than 5 Myr. These clusters do not harbor stars that produce a significant number of photons to ionize He into He⁺; therefore, the ratio should be zero. CSF models lasting for more than 5 Myr predict a He I λ4471/Hβ ratio that is constant with time because after this age, the number of stars able to ionize He is constant since births and deaths are in equilibrium. The stellar absorption is more important for the higher terms of the Balmer series and for older instantaneous bursts than for the csf scenario (Fig. 16). Hβ is dominated by the stellar absorption if the burst is older than 8 Myr; however, the effect of the stellar absorption is small if the star formation proceeds continuously. Thus, at 100 Myr, the strength of the Hβ stellar absorption is less than 20% of the strength of the nebular emission. However, the effect of the stellar absorption is more dramatic for the higher terms of the Balmer series. Hδ and H8 are dominated by the stellar absorption if the burst is older than 4 and 5 Myr, respectively. If the star formation proceeds continuously, after 30 and 100 Myr, the strengths of the stellar absorption lines are equal to those of the nebular emission lines H8 and Hδ, respectively.

The He I nebular emission lines are more affected by the stellar absorption lines than the hydrogen Balmer lines (Fig. 17). Bursts older than 5 Myr do not show He I emission, and after this age, they can be in absorption (Fig. 17a). He I λ3819 is more affected by the stellar absorption than the other lines. The equivalent width of the emission line equals the absorption equivalent width when the burst is only 3 Myr old. As with the Balmer lines, He I lines are less affected by the absorption if the star formation proceeds continuously (Fig. 17b). He I λ4471 is very little affected by the absorption; however, the equivalent width of the emission-line He I λ3819 equals the stellar absorption-line equivalent width at 20 Myr for CSF, and after this time He I λ3819 is dominated by the stellar absorption.

Thus, as we anticipated, the high-order terms of the Balmer series and He I λ3819 in absorption are good indicators of the evolutionary state of the starburst because the nebular emission is weaker and the lines are dominated by the stellar component.
These spectra are public (Leitherer et al. 1996). The spectral of stellar clusters in the Large Magellanic Cloud (LMC), the width of the Balmer lines of our models with observations.

5. TESTING THE MODEL RESULTS

In this section, we compare the profile and equivalent width of the Balmer lines of our models with observations of stellar clusters in the Large Magellanic Cloud (LMC), the super-star cluster B in the starburst galaxy NGC 1569, the nucleus of the dwarf elliptical galaxy NGC 205, and a luminous "E + A" galaxy to test the applicability of our models.

5.1. Clusters in the LMC

Bica & Alloin (1986b) observed clusters in the LMC with ages between 10 and 500 Myr. The data were grouped into four different types, called Y1, Y2, Y3, and Y4, corresponding to ages of 10, 25, 80, and 200–500 Myr, respectively. These spectra are public (Leitherer et al. 1996). The spectral range covers 1200 to 9800 Å, with a resolution in the range 7–17 Å. At optical wavelengths, the template Y1 contains the cluster NGC 2004 (age = 8 Myr, [Z] = −0.25); Y2 contains NGC 1847 (age = 25 Myr, [Z] = −0.4), NGC 2157 (age = 30 Myr, [Z] = −0.6) and NGC 2214 (age = 40 Myr, [Z] = −1.2); Y3 contains NGC 1866 (age = 86 Myr, [Z] = −1.2); and Y4 contains NGC 1831 (age = 300 Myr, [Z] = −1.0) and NGC 1868 (age = 500 Myr, [Z] = −1.1).

Figure 18 compares the equivalent width of the Balmer lines of the four templates measured in the same windows as the models. The figures show the model results for a single burst assuming that the mass of the cluster is distributed with a Salpeter IMF between 1 and 80 $M_{\odot}$ at $Z_{\odot}$ (full line) and $Z = 0.001$ (dashed line) metallicity. The observations and the models are in very good agreement. However, the equivalent widths of the higher terms of the Balmer series of

**Table 7**

| Age (Myr) | Q | L(H$\beta$) | H$\beta$ | H$\gamma$ | H$\delta$ | H$\epsilon$ | H$\alpha$ | $\lambda$4471 $/ H\beta$ | $\lambda$4471 | $\lambda$4026 | $\lambda$3819 |
|-----------|---|------------|---------|----------|----------|-----------|----------|----------------|-----------|-----------|-----------|
| 0 – 10    | 0.046 | 134 | 22 | 5.3 | 14.7 | 5.3 | 2.6 |
| 1 – 20    | 0.045 | 134 | 22 | 5.3 | 14.7 | 5.3 | 2.6 |
| 2 – 50    | 0.037 | 102 | 16 | 3.2 | 8.8 | 3.1 | 1.5 |
| 50 – 100  | 0.032 | 102 | 16 | 3.2 | 8.8 | 3.1 | 1.5 |
| 100 – 200 | 0.028 | 102 | 16 | 3.2 | 8.8 | 3.1 | 1.5 |

**Table 8**

| Age (Myr) | Q | L(H$\beta$) | H$\beta$ | H$\gamma$ | H$\delta$ | H$\epsilon$ | H$\alpha$ | $\lambda$4471 $/ H\beta$ | $\lambda$4471 | $\lambda$4026 | $\lambda$3819 |
|-----------|---|------------|---------|----------|----------|-----------|----------|----------------|-----------|-----------|-----------|
| 0 – 10    | 0.046 | 134 | 22 | 5.3 | 14.7 | 5.3 | 2.6 |
| 1 – 20    | 0.045 | 134 | 22 | 5.3 | 14.7 | 5.3 | 2.6 |
| 2 – 50    | 0.037 | 102 | 16 | 3.2 | 8.8 | 3.1 | 1.5 |
| 50 – 100  | 0.032 | 102 | 16 | 3.2 | 8.8 | 3.1 | 1.5 |
| 100 – 200 | 0.028 | 102 | 16 | 3.2 | 8.8 | 3.1 | 1.5 |

Notes:—Col. (1): Age (Myr). Col. (2): Logarithm of the number of Lyman continuum photons ($\lambda^{-1}$). Col. (3): Logarithm of the H$\beta$ luminosity (ergs s$^{-1}$). Col. (4): Line ratio of the nebular emission lines H$\beta$ $/ H\gamma$. Cols. (5)–(8): Equivalent width of the Balmer lines (H$\beta$, H$\gamma$, H$\delta$, and H$\epsilon$, respectively). Cols. (9)–(12): Equivalent width of the nebular emission He i lines ($\lambda$4922, $\lambda$4471, $\lambda$4026, and $\lambda$3819).
the template Y4 (age = 200–500 Myr) are weaker than in the models (Fig. 18, top right and bottom right). The discrepancy could be related to the poor spectral resolution of the observations. Decreased spectral resolution artificially decreases the continuum level, thus decreasing the equivalent width of the observed lines. This effect is more important for template Y4 because the Balmer lines are stronger and broader for ages between 200 and 500 Myr.

5.2. Super–Star Cluster B in NGC 1569

Super–star clusters (SSCs) are highly compact (diameter a few pc), massive ($10^5$–$10^6 M_\odot$), young (age younger than 1 Gyr) clusters. There are suggestions that SSCs represent the present-day analogs of young globular clusters because their masses and sizes are comparable to those of Milky Way globular clusters (O’Connell, Gallagher, & Hunter 1994; Ho & Filippenko 1996). They represent a basic mode of star formation in starburst galaxies (Meurer et al. 1995) and are building blocks of these objects. The clusters can be approximated by a coeval, single metallicity stellar population.

_Hubble Space Telescope_ images of the dwarf starburst galaxy NGC 1569 suggest that the SSC B has an age of 15–300 Myr (O’Connell et al. 1994), and ground-based optical spectra suggest an age of 10 Myr (González Delgado et al. 1997). The latter result is based on the analysis of the optical spectral energy distribution and on the strength of the Ca II triplet (see also Prada, Greve, & McKeith 1994). To test our models, we have compared the synthetic profiles of the Balmer lines with the observations (see González Delgado et al. 1997 for details of the observations). The models are binned to the spectral resolution of the observations (the dispersion is 1.4 Å pixel$^{-1}$). The Balmer lines are partially filled with nebular emission; therefore, the fitting has to be done based on the wings of the absorption features. This effect is less important for the higher terms of the Balmer series because the nebular emission drops quickly with decreasing wavelength. Figure 19 plots the observed lines and the synthetic models for a burst of 10 and 50 Myr at $Z_\odot/5$ metallicity (assuming Salpeter IMF, $M_{low} = 1 M_\odot$ and $M = 80 M_\odot$). The profiles indicate that the Balmer lines are more compatible with a 10 Myr old burst than with one that is 50 Myr old. Ages older than 10 Myr produce profiles that are wider than the observed ones. This comparison confirms the result of González Delgado et al. (1997) that the age of the SSC B is about 10 Myr and shows that this technique can discriminate well between a young and an intermediate-age population.

5.3. The Nucleus of NGC 205

We have observed the nucleus of the dwarf elliptical galaxy NGC 205 to provide a spectral template of an intermediate-age population in order to analyze the stellar popu-
Fig. 18.—Equivalent width of the Balmer lines (top left) Hβ, (bottom right) Hγ, (top right) Hδ, and (bottom right) H8 of an instantaneous burst formed following a standard Salpeter IMF at solar (continuous line) and Z = 0.001 (dashed line) metallicity. The equivalent widths of the templates Y1 (∼10 Myr old), Y2 (∼25 Myr old), Y3 (∼80 Myr old), and Y4 (∼200–500 Myr old) in the LMC are plotted as circles. Horizontal lines indicates the equivalent widths of the Balmer lines measured in the spectrum of the “E + A” galaxy reported by Oegerle et al. (1991).

lation of a sample of Seyfert 2 nuclei (González Delgado et al. 1998). The equivalent widths of the Balmer lines measured in our spectrum [EW(Hβ) = 7.7 Å, EW(Hγ) = 7.4 Å, EW(Hδ) = 8.8 Å, and EW(H8) = 7.4 Å] are weaker than the values predicted by a population in the range 100–500 Myr (see Fig. 14). Bica, Alloin, & Schmidt (1990) have undertaken the population synthesis of the integrated optical light of the nucleus of NGC 205. They conclude that the dominant population is in the range 100–500 Myr; however, this population produces only ∼50% of the optical light. The remaining 50% is due to young (∼10 Myr), intermediate (1–5 Gyr), and old (∼10 Gyr) components that contribute with 10%, 20%, and 20% of the optical light, respectively. These populations have equivalent widths of the Balmer lines that are weaker than the intermediate population of 100–500 Myr (at these ages, the Balmer lines have their maximum strength). Thus, the equivalent width of the Balmer lines is diluted by the contribution of the other components with respect to a single population of several hundred Myr. We have combined our models contributing to the total light in the fraction derived by Bica et al. (1990), and we found that the combined synthesis profile fits very well the observations (Fig. 20).

5.4. A Luminous “E + A” Galaxy

Oegerle, Hill, & Hoessel (1991) reported the serendipitous discovery of a relatively low redshift galaxy in the poststarburst phase that is one of the best examples of the “E + A” galaxies (Dressler & Gunn 1983). The spectra of these galaxies show very strong Balmer absorption lines produced by a large number of A stars. These stars result from a burst of star formation that probably occurred ∼1 Gyr ago and are mixed with the underlying old stellar population typical of an elliptical galaxy.

The equivalent widths of the Balmer lines measured in the spectrum of the “E + A” galaxy discovered by Oegerle et al. (1991) are EW(Hβ) = 9.5 Å, EW(Hγ) = 10.6 Å, EW(Hδ) = 8.7 Å, and EW(H8) = 8.6 Å. These values are plotted as a horizontal dotted lines in Figure 18. With the exception of Hδ, the strength of the Balmer lines indicates that the galaxy is dominated by a population of A stars. The equivalent widths of the lines are well fitted by a burst that occurred in the galaxy 10^8–10^9 yr ago. Profile shapes in spectra of higher resolution could discriminate between the 10^8 and 10^9 yr age.

6. SUMMARY AND CONCLUSIONS

We have computed evolutionary synthesis models that predict high-resolution spectra of a stellar population in the wavelength ranges 3720–3920, 3990–4150, 4300–4400, 4420–4580, and 4820–4950 Å. These models predict the absorption-line profiles of the hydrogen Balmer series (Hβ, Hγ, Hδ, H9, H10, H11, H12, and H13) and the neutral helium lines (He i λ4922, He i λ4388, He i λ4144, He i λ4121, He i λ4026, He i λ4009, and He i λ3819) as a function of the age, IMF parameters, and metallicity in two different star formation scenarios: an instantaneous burst and star formation proceeding continuously at a constant rate.
Models are generated using the isochrone synthesis method assuming that stars evolve from the ZAMS following the set of evolutionary tracks of the Geneva group. At each age, the spectrum is computed assigning the corresponding high-resolution spectrum from our stellar library to each star. The library was computed assuming that the atmosphere of the stars hotter than 25,000 K is in NLTE and cooler stars in LTE and spans a range of $T_{\text{eff}}$ between 50,000 and 4000 K and gravity $0.0 \leq \log g \leq 5.0$ (see Paper I for details).

The computed profiles of the Balmer and He I lines are useful for comparison with spectra of star-forming regions. High spectral resolution profiles of these lines (in the models and observations) are required to constrain the evolutionary state of a very young stellar population through the analysis of the Balmer absorption wings under the nebular emission lines. Evolutionary synthesis profiles of the higher terms of the Balmer series are very useful, as anticipated, to age-date the starburst because the nebular Balmer decrement decreases very rapidly with decreasing wavelength whereas the equivalent widths of the lines are almost constant: $H_\beta$, $H_\gamma$, and $H_\delta \approx 3 \, \AA$, and $H_\alpha$ and $H10 \approx 2 \, \AA$, respectively. The Balmer lines are always weaker than $6 \, \AA$ if the starburst is in the nebular phase (younger than 10 Myr old). Balmer lines are also sensitive to the change of the IMF parameters during the first 4 Myr of the evolution of the starburst. Stronger lines are formed in the cluster if the mass of the cluster is distributed following a truncated Salpeter IMF with $M_{\text{up}} = 30 \, M_\odot$ or if the IMF is steeper than Salpeter. However, the strength of the lines is less sensitive to the low-mass cutoff, contrary to previous suggestions. Balmer lines are prominent ($\approx 2 \, \AA$) even when the low-mass cutoff is as high as $10 \, M_\odot$. Weaker lines are formed if the slope of the IMF is flatter than Salpeter because more massive stars are formed, which have weaker Balmer lines than early-type B stars. However, this effect is important only in the first few Myr of the evolution of the starburst when massive stars are still on the main sequence.

He I lines are also sensitive to the evolution of the starburst. They increase (but not monotonically) with age until about 30–50 Myr; after this age, they decrease. No He I lines are formed after 100 Myr because stars hotter than B8
Fig. 20.—Normalized optical spectrum of the nucleus of NGC 205 (continuous line) observed at the 4 m telescope in KPNO with a dispersion of 1.4 Å pixel$^{-1}$. The composite synthetic normalized spectrum was obtained by adding instantaneous burst models that contribute by the following fractions: 10% of a young ($\approx 10$ Myr old), 50% of an intermediate ($\approx 300$ Myr old), 20% of a moderately old ($\approx 1$ Gyr old), and 20% of an old ($\geq 10$ Gyr) population.

have evolved from the main sequence, and stars cooler than B8 ($\approx 12,000$ K) do not show He I lines. The equivalent widths of He I $\lambda 4471$ and He I $\lambda 4026$, which are the strongest He I lines, range between 0.5 and 1.1 Å. During the first 4 Myr of the evolution of the starburst, the strength of these lines is constant ($\approx 0.5$ Å for He I $\lambda 4471$ and He I $\lambda 4026$ and 0.3 Å for He I $\lambda 4929$, He I $\lambda 4388$, and He I $\lambda 3819$). We estimate that the correction to the He I $\lambda 4471$ nebular emission lines owing to the underlying absorption is between 5% and 25% if the nebular emission has an equivalent width between 10 and 2.5 Å (a young burst). The He I lines are sensitive to the IMF parameters in the same way as the Balmer absorption lines.

For continuous star formation, the strength of the Balmer lines increases with time until 500 Myr. The equivalent widths of the He I lines increase with time until 100 Myr; then they turn over. The equivalent width of the stellar absorption lines ranges between 3 and 10 Å and 0.5 and 0.9 Å for the Balmer and He I lines, respectively. The higher order Balmer absorption lines are more useful to age-date starbursts than H$\beta$ because the latter is mainly dominated by the nebular emission; in contrast, H$\beta$ is dominated by the stellar absorption if continuous star formation lasts for more than 30 Myr. He I $\lambda 3819$ is also very useful to age-date starbursts because the line is dominated by the stellar absorption if continuous star formation lasts for more than 20 Myr.

The advantages of using Balmer and He I lines in absorption to date starbursts with respect to using nebular emission lines are twofold: (1) the age can be constrained in a much wider range, including the nebular and the postnebular phases; and (2) the strengths of the absorption lines are not affected by extinction or by the leaking of ionizing photons. The models have been tested by comparing the strength of the Balmer lines with those of the stellar clusters in the LMC, SSC B in NGC 1569, the nucleus of NGC 205 and a luminous “E+A” galaxy. Very good agreement is found. The full set of models is available at our websites or on request from the authors.

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