A NEW CHEMO-EVOLUTIONARY POPULATION SYNTHESIS MODEL FOR EARLY-TYPE GALAXIES. II. OBSERVATIONS AND RESULTS

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ABSTRACT

We present the results of applying a new chemo-evolutionary stellar population model, developed in a previous paper, to new high-quality observational data of the nuclear regions of two representative elliptical galaxies and the bulge of the Sombrero galaxy. Here we fit in detail ~20 absorption lines and six optical and near-infrared colors, following two approaches: fitting a single-age, single-metallicity model and fitting our full chemical evolutionary model. We find that only the strongest lines can be used to obtain results of problems in, e.g., stellar evolution theory. Finally, we discuss the results obtained by fitting the data. Finally, in this paper, we apply our spectrophotometric population synthesis model following both the single-age, single-metallicity and the chemical evolutionary approaches. We address here the problem of whether the conclusions we obtain depend upon the stellar population synthesis method that we use. In the end we find that the use of many indices does yield interesting information, and we show that we can learn more than by using only a few indices, as has been done before.

1. INTRODUCTION

The study of the stellar populations and the distribution of metallicities plays an important role in our understanding of the star formation history of the galaxies. Their stellar populations are expected to be more complex than those of, for example, globular clusters, which are thought to be composed of a single stellar population. In fact, Burstein et al. (1984) found differences when comparing colors and spectroscopic features of globular clusters with those of galaxies. Key parameters in the interpretation of the observed colors and the line strengths are the metallicity and the age. The problem is that, even in the simplest unresolved stellar systems, their effects are very difficult to separate using only colors (O'Connell 1986; Renzini 1986; Buzzoni, Gariboldi, & Mantegazz 1992).

Using colors together with absorption lines, more accurate conclusions can be drawn. Although every absorption line strength is dependent upon different kinds of stars, in principle it should be possible to determine average metallicities or ages by carefully selecting some features that are more sensitive to the metallicity and others that are more sensitive to the age (see, e.g., Worthey, Faber, & Gonzalez 1992). However, the abundances of some elements may well evolve differently from those of others (e.g., $\alpha$-enhancement), and the conversion of ages and metallicities through models to observed colors and indices may be not unique, as a result of problems in, e.g., stellar evolution theory. Finally, the large velocity broadening in giant elliptical galaxies implies that only the strongest lines can be used to obtain physical information from their spectra.

In the process of understanding the stellar population of early-type galaxies, we first developed a new spectrophotometric model, which can be used to interpret observed colors and absorption lines of galaxies (Vazdekis et al. 1996, hereafter Paper I). The model is based on the latest improvements in stellar evolution theory and on the most recent stellar libraries. Instead of studying a large sample of galaxies using a few line indices, as has been done before (e.g., Worthey et al. 1992; Gonzalez 1993), we preferred to obtain high-quality observations of three representative early-type galaxies (two giant ellipticals and the bulge of the Sombrero galaxy), but in many colors and absorption lines, and to make very detailed fits to each index, to better understand global ages and metallicities and also to follow the abundances of individual elements. Such analysis now is possible since we could calibrate our observations using the large sample of stars from the extended Lick system (Worthey et al. 1994, hereafter WFGB).

In this paper, we apply our spectrophotometric population synthesis model following both the single-age, single-metallicity and the chemical evolutionary approaches. We address here the problem of whether the conclusions we obtain depend upon the stellar population synthesis method that we use. In the end we find that the use of many indices does yield interesting information, and we show that we can learn more than by using only a few indices, as has been done in the past. At the same time, we study the stellar population gradients in the three galaxies.

This paper is organized as follows: In § 2, we explain our observations and the method that we use to derive the line strengths. In § 3, we fit our population synthesis model and discuss the results obtained by fitting the data. Finally, in § 4 we present our conclusions.

2. OBSERVATIONS AND DATA REDUCTION

2.1. Observations

Long-slit spectra of three well-known early-type galaxies were obtained with the ISIS spectrograph on the 4.2 m William Herschel Telescope in 1995 March, at the Observatorio del Roque de los Muchachos, La Palma. The spectra were taken using both arms of the instrument, with
a large-format Tek CCD chip windowed to 1124 \times 600 pixels, each with a size of 24 \mu m. In the blue we used a grating of 600 lines mm\(^{-1}\) yielding a sampling of 0.79 \AA\ pixel\(^{-1}\), while in the red we used a 300 line mm\(^{-1}\) grating yielding a sampling of 1.46 \AA\ pixel\(^{-1}\). Our spectra were taken in the range 3700–6300 \AA. This configuration allowed us to cover almost the whole set of the absorption features contained in WFGB, in addition to some UV features as defined by Pickles (1985). In fact, in the blue arm we covered the range 3700–4500 \AA, while in the red arm we covered the range 4800–6300 \AA. We could not observe the Ca4455, Fe4531, and Fe4668 features because they fall in the cross-over region of the dichroic. The measured resolution was \sim 3.4 \AA\ in the blue and \sim 6.5 \AA\ in the red spectra. We also lost the TiO\(_2\) feature since this index falls at the limit of the range covered. A set of stars from the sample of WFGB was also observed in order to calibrate our line-strength measurements. We positioned the slit on the major axis for NGC 4472, at 123\(^\circ\) for NGC 3379 (the major axis is at \sim 70\(^\circ\); see Peletier et al. 1990a), and on the minor axis for the Sombrero galaxy (NGC 4594). The exposure times were 1800 s for both frames.

2.2. Data Reduction

All data reduction was performed with the IRAF software package. The first step was subtracting the bias value calculated from the unilluminated portion of each frame. After this we flat-fielded using tungsten lamp exposures. Next, the spectra were wavelength-calibrated using CuAr + CuNe calibration lamp exposures. The obtained pixel scale was 57.535 km s\(^{-1}\) pixel\(^{-1}\) for the blue and 79.926 km s\(^{-1}\) pixel\(^{-1}\) for the red spectra. The following step was the sky subtraction, for which the outer parts of each galaxy frame (chosen at approximately 2′ from the center of the galaxy) were averaged to produce a mean sky spectrum, which then was subtracted from each frame. The last step was the elimination of pixels affected by cosmic rays in each frame.

2.3. Line-Strength Measurements

We need a well-defined way to assign values to the strengths of features at different radii in the galaxy. For this purpose, we used the expanded Lick system (WFGB). Here some indices (the atomic features) are defined as equivalent widths and some (the molecular bands) as ratios of line depth to continuum in magnitudes, and we have maintained these definitions. To measure these line-strength indices along the major axis, we had to deredshift each feature and the continuum on each side of it by using the recession velocity corresponding to each spectrum. To calculate the rotation curve, the spectra at each radius were cross-correlated with the observed spectrum of a stellar velocity standard star that looks most like the galaxy (with spectral type K III; see § 2.3.1). This method is described by Bottema (1988), following the paper of Tonry & Davis (1979). Then we calculated the indices by adding a sufficient number of spectra in the spatial direction so that a satisfactory continuum level was reached across the whole wavelength range. More details about the indices can be found in WFGB and Burstein et al. (1984).

2.3.1. Conversion to the Expanded Lick System

Since we want to compare our data with the spectro-photometric model developed in Paper I, which is based on the Lick system, we need to transform our results to that system. Among the problems encountered in achieving this are the fact that the instrument that we used (ISIS) has a different spectral response, the fact that WFGB did not flux-calibrate their stars, and the higher resolution of our data (\sigma \sim 125 km s\(^{-1}\) in the blue and \sim 145 km s\(^{-1}\) in the red spectra) compared with theirs (\sim 200 km s\(^{-1}\)). While the effect of a different instrumental response is almost negligible in the narrow indices, it is important in the broader ones such as Mg\(_2\), since both the index itself and the two pseudocontinua cover a wide range in wavelength. On the other hand, the effect of having higher resolution is important only in the narrower indices, which are affected in the same way as by the velocity dispersion broadening. Therefore, to transform our indices to the expanded Lick system we first prebroadened both spectra, the galaxy and the reference stars, so as to match the resolution of the Lick system. Next we compared the thus obtained line-strength measurements of our stars with those given in WFGB to find an empirical average correction constant for each feature (see Table 1). In particular, the stars used for this conversion were HR 3461 (K0 III), HR 4521 (K3 III), and HR 4932 (G8 III) (for details, see WFGB). We attribute the large correction factor found for the Fe4383 feature to the fact that its right-hand pseudocontinuum falls at the edge of our observed spectra, entering the crossover wavelength region of the dichroic used in the observations. The large correction constant for Ca4227 is mainly due to the fact that this line is weak and the number of stars used for the conversion is small. As expected, we see that the most important correction constants are those obtained for the molecular features.

2.3.2. Correction for Velocity Dispersion of the Galaxies

To correct the measured indices for instrumental resolution and the velocity dispersion of the galaxy, we used

| Table 1 |
| --- |
| **Correction Factors** |
| **Index** | **Velocity Dispersion** | **Conversion to Lick** |
| UV CN .......... | 1.002 | ... |
| Ca H + K ...... | 1.016 | ... |
| Fe t + CN ...... | 1.030 | ... |
| CN\(_1\) .......... | 1.036 | \(-0.028\) |
| CN\(_2\) .......... | 1.046 | \(-0.041\) |
| Ca4227 ......... | 1.334 | \(-0.35\) |
| G band .......... | 1.032 | 0.11 |
| Fe4383 .......... | 1.074 | \(-2.95\) |
| H\(\beta\) .......... | 0.988 | 0.0 |
| Fe5015 ......... | 1.132 | 0.37 |
| Mg\(_b\) .......... | 1.016 | \(-0.058\) |
| Mg\(_c\) .......... | 1.006 | \(-0.053\) |
| Fe5270 .......... | 1.134 | 0.16 |
| Fe5335 .......... | 1.253 | 0.22 |
| Fe5406 .......... | 1.234 | \(-0.05\) |
| Fe5709 .......... | 1.129 | 0.0 |
| Fe5782 .......... | 1.242 | 0.0 |
| Na D .......... | 1.062 | 0.29 |
| TiO\(_b\) .......... | 1.067 | 0.006 |

**Notes.**—Correction factors for velocity dispersion (the given values correspond to NGC 4472 at 5°, calculated in equivalent width) and for the conversion to the expanded Lick system (in angstroms except for the CN, CN\(_2\), Mg\(_b\), Mg\(_c\), and TiO\(_b\) indices, which are given in magnitudes). The velocity dispersion correction factors are defined in § 2.3.2, while the conversions to the Lick system are constant quantities to be added to the measured indices.
Fig. 1.—Plot of the different indices of NGC 3379, obtained for a position angle of 123°. Filled and open symbols indicate the values at each side of the center, respectively. We also have included linear fits (see Table 3). The error bars shown here include all errors discussed in the text except the conversion to the extended Lick system, which is shown in the bottom left corners.

the spectra of a few K giants from the sample of WFGB to calibrate their effects on the galaxy indices in the same way as has been done before by, e.g., Davies, Sadler, & Peletier (1993). An autocorrelation of the central spectrum of each galaxy yielded its corresponding broadening, which includes both the instrumental and the real velocity dispersion. After this we convolved the prebroadened stellar spectrum with a Gaussian of width $\sigma_p$ calculated to match that
observed in the galaxy. The velocity dispersion of this Gaussian was (in pixels)
\[ \sigma_p = \sqrt{\sigma_G^2 - \sigma_0^2 / \Delta v}, \]
where \( \sigma_0 \) is the observed velocity dispersion of the galaxy, \( \sigma_0 \) is the measured instrumental profile (obtained by cross-correlation of the star with itself), and \( \Delta v \) is the conversion factor in km s\(^{-1}\) pixel\(^{-1}\) (see § 2.2). For each index \( i \) an empirical correction factor, \( C_i(\sigma) \), defined as \( i(\sigma)/i(0) \), was determined for all these stars. We performed this step by calculating all the indices in equivalent width, and never in magnitudes. The resulting \( C_i(\sigma) \) was found by taking the
mean of the measured correction factors (see Table 1). From a quick look at these factors we see that, in general, the higher the resolution and the weaker the feature, the higher the correction. For example, the weakest line in the blue spectra, the Ca4227, shows the highest correction (see also Fig. 13 below), while in the red spectra this is the case for some of the iron features.

Finally, the calculated velocity dispersions amounted to 250 km s$^{-1}$ for NGC 3379, 320 km s$^{-1}$ for NGC 4472, and 280 km s$^{-1}$ for the Sombrero. These values are not very
The line-strength measurements for the three galaxies are shown in Figures 1–6. We see appreciable gradients for most of the indices. However, we detect only weak gradients for Hβ, the G band, and the weakest lines: Ca4227, Fe5709,
and Fe5782. The low slopes in Hβ were found useful for constraining galaxy formation scenarios by Fisher, Franz, & Illingworth (1995). In the next sections we will concentrate on the study of the nuclear regions of these galaxies, as well as on their gradients. To study the inner regions, we have selected values for the indices corresponding to 5′ from the center, and to study radial gradients, we also selected values at 15′. We did not go further inward, because our seeing was poor (∼3′), to avoid possible nuclear emission lines (see, e.g., Goudfrooij & Emsellem 1996; Boroson &
In Figure 7, we give a comparison with the data from the current literature for NGC 4472. Our Mg$_2$ index is slightly lower than the values of the other authors, but we are in better agreement with the data of Saglia et al. (1993). For H$\beta$ the agreement is generally good, while our $\langle$Fe$\rangle$ values fall in the middle range of other observations. For the sake of brevity, we have not shown other comparisons, but, for example, for NGC 3379 our Mg$_2$ and H$\beta$ indices obtained
are in very good agreement with Davies et al. (1993), while their \(<\text{Fe}\)> is higher than ours.

### 2.4. Determination of the Errors

The main sources of error are the Poisson noise, the error in the adopted zero point of the calculated rotation curve (used to deredshift the spectra), the chosen velocity dispersion correction factors, and the transformation to the extended Lick system.

A quantitative estimate of the photon counting statistics has been carried out, following the error analysis of spectroscopic features by Rich (1988). The error in equivalent width is

\[
\sigma(W) = \frac{\Delta \lambda N_1}{\bar{c}} \left[ \frac{1}{N_1} + \left( \frac{\sigma_c}{\bar{c}} \right)^2 \right]^{1/2},
\]

where \(\Delta \lambda\) is the dispersion, \(\sigma_c\) is the error in fixing the continuum, \(N_1\) is the total number of counts in the line bandpass (including negative counts), and \(\bar{c}\) is the mean continuum at the feature, defined as the value of the continuum point interpolated between the two continuum bands at either side of the feature. The \(\sigma(W)\) translates to a magnitude error \(\sigma(m)\):

\[
\sigma(m) = -2.5 \log e \left[ \frac{1}{N_1} + \left( \frac{\sigma_c}{\bar{c}} \right)^2 \right]^{1/2}.
\]

The uncertainty caused by the adopted zero point of the rotation curve was estimated by calculating the rotation curves separately for each star and then comparing the differences in the obtained line strengths. The errors due to the correction for velocity dispersion and the conversion to the Lick system were estimated in the same way, by looking at the dispersion in the line strengths obtained from different stars. Typical errors of the various types are listed in Table 2. Here one can note that in general the conversion to the expanded Lick system introduces the most important uncertainty. This error is mainly due to the low resolution of the Lick data, and therefore we are assuming their uncertainties. In Figures 1–6 and in Figure 7, this error is given.
separately from the others in the corners of the individual panels (see also Table 3).

3. FITTING THE EARLY-TYPE GALAXIES

In this section we apply the spectrophotometric population synthesis model developed in Paper I, which was especially designed to study early-type galaxies. Briefly, the model makes predictions for the optical and IR colors and 25 absorption-line indices. It is based on the new theoretical isochrones of Bertelli et al. (1994) (calculated with solar abundance ratios), but converted to the observational plane by using empirical calibrations of individual stars (see Paper I for details). To calculate line strengths, it uses the latest stellar spectral libraries (mainly WFGB). The model calculates the properties of a stellar system starting from a primordial gas cloud and calculating the chemical evolution in a way that broadly follows the mathematical formalism of Arimoto & Yoshii (1986). The model can also be used to obtain the integrated colors of a single-age, single-metallicity stellar population (SSP). In this work, we will use both schemes. First we will apply an SSP model and obtain the integrated colors of a single-age, single-metallicity population (SSP). In this work, we will use both schemes. First we will apply an SSP model and obtain the integrated colors of a single-age, single-metallicity stellar population (SSP). In this work, we will use both schemes. First we will apply an SSP model and obtain the integrated colors of a single-age, single-metallicity population (SSP).

3.1. Fitting with the Single-Age Stellar Population Model

Using the \((V-K)\)-Mg\(_{2}\) and \((B-V)\)-Mg\(_{2}\) diagrams, we showed in Paper I that to fit this set of galaxies solar metallicities or larger values are required. In Figure 8, we plot a number of color-color diagrams. In Figure 9 we have selected two key colors, \(B-V\) and \(V-K\), and plotted a representative feature of each element versus these colors. Finally, in Figure 10 we have plotted various index-index diagrams, and since the number of features is large, we selected as references for these plots three of the most commonly used indices in the literature, \(H\beta\), Mg\(_{2}\), and \(\langle Fe \rangle\). To obtain these figures, we used the two forms of the initial mass function (IMF) defined in Paper I: the unimodal IMF, with a power law of slope \(\mu \) as a free parameter (where 1.35 corresponds to the Salpeter value), and a bimodal IMF, which is equal to the unimodal IMF above 0.6 M\(_{\odot}\) but reduces the influence of stars with masses below 0.6 M\(_{\odot}\). The two IMFs used here have a lower mass cutoff of 0.1 M\(_{\odot}\) and an upper mass cutoff of 72 M\(_{\odot}\). Looking at the respective diagrams in these figures, we see that a difference between models using the two IMFs is evident only in the redder spectral indices, such as TiO\(_{1}\), and the redder colors, such as \(V-K\). Of course, the unimodal IMF gives us higher line strengths since the number of low-mass stars is higher and, therefore, the relative number of diluting blue stars is lower.

Looking at all these figures, but excluding those diagrams that contain iron features, we infer that to fit this set of galaxies we need either solar metallicity and very high ages (say, 15 Gyr or even more) or metallicities that are higher than solar and lower ages (around, say, 8 Gyr) but never very low ages. We also see that the colors seem to be best fitted using metallicities lower than those used for line strengths since the number of low-mass stars is higher and, therefore, the relative number of diluting blue stars is lower.

| Index      | Poisson Error | Rotation Curve Error | Velocity Dispersion Error | Conversion to Lick Error |
|------------|---------------|----------------------|---------------------------|-------------------------|
| UV CN      | 0.87          | 0.35                 | 0.03                      | ...                     |
| Ca H + K   | 0.44          | 0.06                 | 0.02                      | ...                     |
| Fe i + CN  | 0.45          | 0.15                 | 0.05                      | ...                     |
| CN         | 0.005         | 0.001                | 0.001                     | 0.017                   |
| Ca4227     | 0.11          | 0.06                 | 0.04                      | 0.23                    |
| G band     | 0.15          | 0.09                 | 0.03                      | 0.30                    |
| Fe4383     | 0.25          | 0.09                 | 0.06                      | 0.46                    |
| H\beta     | 0.17          | 0.06                 | 0.0                        | 0.16                    |
| Fe5015     | 0.36          | 0.30                 | 0.02                      | 0.33                    |
| Mg\(_{2}\) | 0.003         | 0.002                | 0.0                        | 0.005                   |
| Mg\(_{2}\) | 0.002         | 0.003                | 0.001                     | 0.006                   |
| Mg\(_{2}\) | 0.17          | 0.09                 | 0.06                      | 0.17                    |
| Fe5270     | 0.17          | 0.08                 | 0.02                      | 0.20                    |
| Fe5335     | 0.18          | 0.08                 | 0.02                      | 0.21                    |
| Fe5406     | 0.15          | 0.03                 | 0.01                      | 0.14                    |
| Fe5709     | 0.09          | 0.08                 | 0.01                      | 0.13                    |
| Fe5782     | 0.09          | 0.15                 | 0.0                        | 0.15                    |
| Na D       | 0.11          | 0.22                 | 0.05                      | 0.21                    |
| TiO\(_{1}\) | 0.003         | 0.001                | 0.001                     | 0.005                   |

Notes.—Uncertainties in the indices due to photon statistics (Poisson), the selected rotation curve zero point, the velocity dispersion, and the conversion to the expanded Lick system. The given photon error is an average value calculated at \(\sim 5^\circ\) from the centers of the three galaxies.
the line strength is given by $a + b \log r$, where $r$ is in arcseconds; $\epsilon$ represents the formal errors.

**TABLE 3**

| Index       | $a$   | $\epsilon(a)$ | $b$   | $\epsilon(b)$ |
|-------------|-------|---------------|-------|---------------|
| UV CN       | 33.622| 0.2918        | -3.6227| 0.3837        |
| Ca H + K    | 25.4420| 0.3357        | -2.9515| 0.4413        |
| Fe 1 + CN   | 13.1877| 0.2556        | -6.8013| 0.2299        |
| CN          | 0.1302| 0.0023        | -0.0639| 0.0029        |
| CN          | 0.1474| 0.0032        | -0.0733| 0.0046        |
| Ca4227      | 0.7547| 0.0411        | -0.0238| 0.0519        |
| G band      | 5.3519| 0.0775        | -0.3650| 0.1019        |
| Fe4383      | 5.5943| 0.2005        | -1.2002| 0.2532        |
| H$\beta$    | 1.5859| 0.0597        | -0.3210| 0.0746        |
| Fe5015      | 5.4273| 0.1132        | -1.0814| 0.1454        |
| Mg$b$       | 0.1765| 0.0025        | -0.0455| 0.0032        |
| Mg$b$       | 0.3419| 0.0038        | -0.0791| 0.0047        |
| Mg$b$       | 5.0203| 0.0822        | -1.0044| 0.1029        |
| Fe5270      | 3.2075| 0.0583        | -0.5363| 0.0729        |
| Fe5335      | 2.6466| 0.0394        | -0.4522| 0.0493        |
| Fe5406      | 1.7023| 0.0308        | -0.3325| 0.0385        |
| Fe5709      | 0.7610| 0.0277        | -0.1625| 0.0346        |
| Fe5782      | 0.7529| 0.0364        | -0.2218| 0.0391        |
| Na D        | 3.5155| 0.0434        | -1.3884| 0.0542        |
| TiO         | 0.0477| 0.0012        | -0.0096| 0.0015        |

**TABLE 4**

| Position | Distance (kpc) | Fraction of $r_e$ |
|----------|---------------|-------------------|
| NGC 3379 ($V_e = 889$ km s$^{-1}$, $r_e = 37.5$): | | |
| 50'       | 0.29          | 0.13               |
| 150'      | 0.86          | 0.40               |
| NGC 4472 ($V_e = 983$ km s$^{-1}$, $r_e = 114.0$): | | |
| 50'       | 0.32          | 0.04               |
| 150'      | 0.95          | 0.13               |
| NGC 4594 ($V_e = 1082$ km s$^{-1}$, $r_e = 61.8$): | | |
| 50'       | 0.35          | 0.08               |
| 150'      | 1.05          | 0.24               |

Notes.—The distances from the centers of the galaxies were calculated taking their recession velocities from de Vaucouleurs et al. 1991 and $H_0 = 75$ km s$^{-1}$ Mpc$^{-1}$. The effective radii $r_e$ of the elliptical galaxies were taken from Burstein et al. 1987 as given by Peletier et al. 1990a and, for the Sombrero galaxy, from Hes & Peletier 1993.

the observed indices can be easily fitted when plotted versus $Mg_b$ or $H\beta$, this is not the case when plotted versus the (Fe) index. In the following we will discuss various aspects of the fits.

3.1.1. Iron Features

In Figure 9 we see that all the iron lines from the model are stronger than those observed, and in Figure 10 we see that the models are always able to fit the different index-index plots, except those against (Fe). This suggests that iron is anomalous and deficient compared with the other indices and colors. This shows that solar ratios are not adequate to fit this kind of galaxy, confirming the results of Peletier (1989), Worthey et al. (1992), Gonzalez (1993), and Davies et al. (1993). These results do not depend upon whether we are working with a unique SSP or with a mixture of SSPs of different ages and/or metallicities (as in §3.2), as can be easily inferred from the different Fe versus $Mg_b$ plots. To try to explain these results, we applied some simple models based on the hypothesis of $\alpha$-enhancement.

In reality, this phenomenon in principle affects all the parameters of stellar evolution, and therefore a new set of isochrones ought to be obtained, calculating observables for integrated stellar populations. As a first approximation, we follow the conclusions of Weiss, Peletier, & Matteucci (1995) that for the calculation of $\alpha$-enhanced indices one can use the isochrones calculated for solar abundance ratios, keeping the global metallicity constant but changing the ratios. In Figure 11 we find better solutions for the Mg and Fe indices, but worse for Na (at least with the adopted ratios). For an IMF slope of 1.35, it does not make any difference whether a unimodal or a bimodal IMF is chosen. From the Fe versus $Mg_b$ plots, we see that to fit the data we need [Mg/Fe] in the range 0.3–0.7, in agreement with the results obtained by Weiss et al. (1995). This number does not seem to vary inside each galaxy. To conclude, we find that the metallicity (in terms of $Z$) determined from the Fe lines is different from that determined from the Mg lines.

3.1.2. Ca4227

We left discussion of the Ca4227 line for a separate section since this is the worst-fitting line. In Figure 12, we plot different representative features and the color $V-K$ versus this feature. Apart from our models, we also plot those of Worthey (1994). We see here that the discrepancy between predictions and observations is more dramatic than was found for the iron lines. Independently of the IMF
slopes, age, or metallicity, the Ca4227 line in the three galaxies is much lower than predicted by the models. It has been suggested before by O’Connell (1976) and Worthey (1994) that calcium tracks iron. In fact, in this figure we see that the fits obtained when plotting this line versus $\langle Fe \rangle$ are not as bad as when plotting it versus the other features. Even so, this line cannot be fitted in an acceptable way. Nor is the result due to a deficiency in the supporting library of stars, since for all the other indices (except those dominated by Fe) reasonable fits can be achieved. It looks as if Ca is depleted in this type of galaxy. If, however, we look at other Ca lines, we cannot easily confirm this. We could not observe the Ca4455 feature (a blend containing an important contribution of Ca II) as a result of the wavelength position of the dichroic used for the observations, and the Ca II near-IR triplet seems to contribute only a small depletion. Terlevich, Diaz, & Terlevich (1990) found for NGC 4472 a total EW of $\sim 6.7$ Å for the two strongest lines, corrected for velocity dispersion. If we model this feature using the stellar library of Diaz, Terlevich, & Terlevich (1989) and preserving their definitions (for details, see Paper I), we see that our best-fitting models predict an EW of around 8.0 Å (see Tables 7 and 8 below). This means that we find some depletion, but much less than for the Ca4227 feature.

As can be seen in the Ca4227 versus Mg II diagram of Figure 11, it is easy to understand that an $z$-enhanced scenario does not fit the observed Ca4227, since this feature is almost entirely due to calcium, another $z$-element. The same plot also shows us that, even considering this scenario, the small contribution to this feature by Fe I ($\sim 20\%$, by inspection of the Arcturus atlas [Hinkle, Lloyd, & William 1995]) cannot explain the observed data. Since the $^{48}\text{Ca}$ isotope is much less abundant than $^{40}\text{Ca}$, we also cannot attribute this effect to the fact that $^{48}\text{Ca}$ is not produced in quantities appropriate to its solar abundance and because it is made in Type Ia supernovae (those that ignite a carbon deflagration very near the Chandrasekhar mass), as recently suggested by Woosley & Weaver (1995).

Rose (1984) has measured the Ca II H and K indices in stars, finding that Hyades and Pleiades dwarfs present strong Ca II emission compared with field dwarfs. He suggested that many of the principal absorption features in the blue spectral region are affected by stellar activity. However, in another paper (Rose 1994), he himself measured the Ca4227 line in 47 Tuc and M32 and reached the opposite conclusion to that found here. This suggests that this effect, if it is real, will be present only in bright early-type galaxies, in the same way as Mg tends to be enhanced with respect to Fe in this kind of galaxy. If this result is...
general, it will have important consequences for our knowledge of elemental synthesis in Type II supernovae.

However, we cannot strongly affirm the anomalous behavior of Ca, for two principal reasons. First, Ca4227 is a weak line, and second, because, as one can see from Table 1, its conversion to the extended Lick system entails one of the highest corrections (~0.35). The error in this correction is quite large, as a result of which this depletion formally is only a 2.5σ result. To see whether the depletion is really present, we show in Figure 13 the spectrum of NGC 4472 together with that of the star HR 3461, for which WFGB measured an EW for Ca4227 of 1.05 Å and we measure 0.81 Å, while for the galaxy we find a value of 1.14 Å (the last two EWs converted to the Lick system). For the present we can say only that this will need more study and that observations of the Ca II triplet feature in the near-IR may provide additional help.

3.1.3. All the Synthetic Results Combined into One Value: The Merit Function

Since the number of observables is large, we have implemented a merit function, $M$, defined as

$$M = \sum_{i=1}^{n} H_i \left( \frac{G_i - S_i}{E_{\text{obs},i}} \right)^2,$$

where $S_i$ and $G_i$ are the synthetic and observed variable $i$, respectively, and $E_{\text{obs},i}$ is the corresponding observational error. All these quantities must be expressed in magnitudes to perform the calculation of $M$. Finally, $H_i$ is the assigned weight.
In practice, we determine a separate merit figure for the set of colors $M_{c}$ and for the set of line strengths $M_{l}$. The merit function determines the goodness of a fit for all observables taken together. The problem of optimizing a fit is now reduced to finding a minimum for this merit function. Since the observational errors are nonzero, the code calculates the maximum acceptable value for the merit, $M_{\text{max}}$, using the same equation, but using the observational error instead of $G_i - S_i$. Any solution that yields a value of merit smaller than $M_{\text{max}}$ is in principle acceptable.

In this paper we have assigned the same total weight to the colors and to the lines. Therefore the final global merit is calculated as follows:

$$ M = M_{c} + M_{l} \left( \frac{M_{c,\text{max}}}{M_{l,\text{max}}} \right). $$

### 3.1.4. Best Fits Obtained with a Unique SSP

To find the best solutions we first have to give weights to each color and index. As has been shown before, it is clear that whatever the metallicities, ages, or IMF slopes are we cannot fit the iron lines, possibly because of Fe deficiency. For that reason, in this paper we give a weight of zero to indices composed mainly by iron. We also assign a weight of zero to the Ca4227 absorption line because of its apparently strong depletion. To the other observables we give a weight of 1 except for $\text{CN}_1$ and $\text{CN}_2$, because they are the same index (they differ only in the definition of the blue pseudocontinuum bandpass) and therefore we assign a weight of 0.7 to each instead of 1, so that their global weight is higher than 1 but lower than 2. The given weights are summarized in Table 5 (case A). On the basis of the obser-
Fig. 11.—An $\alpha$-enhanced test diagram using the \([\text{Mg/Fe}] = 0.4 ("\alpha_1")\) and \([\text{Mg/Fe}] = 0.6 ("\alpha_2")\) enhanced mixtures of Weiss et al. (1995). The synthetic values were obtained for a bimodal IMF with slope of 1.35. We plot here different representative features (including three iron lines) vs. These mixtures make our prediction for the iron features better but for the Na D index worse.

vational errors given in Table 2 (excluding the error from the conversion to the expanded Lick system) and the assigned weights, only merits smaller than 10.0 can be considered as acceptable fits. However, as we will see later, the obtained merits are often as high as 20. These numbers are probably still acceptable, since we did not include the systematic uncertainties in converting our indices to the expanded Lick system and systematic errors in the theoretical models.

Using this merit function, we scanned the three-parameter space ($Z$, $\mu$, age) for each galaxy. Since our SSP models make use of isochrones with a large step in metallicity (see Paper I), we made a new grid of synthetic values by interpolating linearly between the output obtained for $Z = 0.008, 0.02$, and 0.05 to obtain the synthetic observables corresponding to $Z = 0.012, 0.016, 0.03$, and 0.04. Figure 14 shows the merit values obtained for NGC 3379 at the two selected positions 5° and 15°. To obtain this figure, we used a unimodal IMF with slopes varying from 0 to 2.3 while the age was varied from 1 to 17 Gyr. We plot the contours and the gray levels for merits that are lower than $\Delta \mu_{\text{max}} = 25.0$. We chose this maximum acceptable limit to be safe and to avoid excluding even moderately possible solutions. In Figure 15 we scanned the same parameter space to fit this galaxy, but using a bimodal IMF. Comparing the two figures it is clear that the unimodal IMF yields worse fits, and for that reason we will work throughout this paper with a bimodal IMF. The same results were found in Paper I using our full chemo-evolutionary population synthesis model. The main difference that we found by looking at the fits obtained with the two IMFs is the fact that the best fits obtained using a unimodal IMF require lower slopes than those obtained with the bimodal IMF. We expect this since the unimodal IMF yields a higher number of low-mass stars (see Paper I). As a general conclusion, we can say that these galaxies cannot be fitted assuming low values for the age. The inner regions of the three galaxies must be metal rich, since merit figures lower than 25.0 are only found for metallicities higher than solar. In particular, NGC 4472 is even more metal rich than the other two galaxies.

3.1.5. Stellar Population Gradients

Looking at Figures 14 and 15, we see that to fit the two selected positions of NGC 3379 we must keep the age
almost constant at values around 13 Gyr, while the metallicity varies from values higher than solar ($Z \sim 0.03$) at $5^\circ$ to lower than solar ($Z \sim 0.016$) at $15^\circ$. We also note that it is not possible to obtain acceptable fits if we maintain the metallicity constant but change the age, the IMF slope, or both. However, this is not the case for NGC 4472 (see Fig. 16), for which we find acceptable solutions if we decrease the age from 10 to 8 Gyr going outward and maintain the metallicity constant at $Z \sim 0.04$. Of course, we also find a fit if we keep the age constant around 10 Gyr but decrease the metallicity from $Z = 0.04$ to $Z = 0.03$ going outward. For the bulge of the Sombrero galaxy (see Fig. 17) a decrease in the metallicity is required when going outward, and no age-variable, metallicity-constant solution will do. We see that this galaxy seems to behave in the same way as NGC 3379, but with ages slightly lower.

We can conclude that the observed radial index gradients are attributable to metallicity gradients rather than gradients in age. The fact that this conclusion cannot be completely verified in NGC 4472 may be explained if we take into account that this galaxy is much larger than the other two, and thus the measured positions represent relatively small fractions of its effective radius (see Table 4).

*Testing for the presence of dust.*—To test for the presence of dust in these galaxies, we have used the simple reddening law of Rieke & Lebofsky (1985) and applied it to the synthetic colors using steps in $A_\beta$ of 0.1 mag. We scanned again the whole parameter space ($Z$, $\mu$, age) and examined the fits using the merit function. We found that the inclusion of dust does not improve the fits, except for the Sombrero galaxy at $15^\circ$, for which we obtained a better fit by including $A_\beta = 0.3$ mag.

### 3.1.6. Mg Overabundant or Fe Deficient?

From the previous color-index and index-index diagrams, we have inferred that the iron lines are not well fitted by the models. However, to be more complete, one might think to include them in the fitting procedure and neglect...
which we have not given any weight to the Fe and Ca lines, the choice of weights used throughout this work (case A), in interpretation of our fits. For that purpose, together with tions to check the validity of our selection, and for a better the magnesium features or take other weighting distributions to check the validity of our selection, and for a better interpretation of our fits. For that purpose, together with the choice of weights used throughout this work (case A), in which we have not given any weight to the Fe and Ca lines, we defined four alternative merit functions. In case B we have taken into account all the iron features and assigned each a weight of 0.43, so that their global weight is 3, the same as the sum of the magnesium features. In case C, instead of neglecting the iron lines as in case A, we gave a weight of zero to the three magnesium lines. In case D we took into account only the iron lines and Hβ and neglected all the other lines. Finally, in case E we neglected both iron and magnesium, as well as the Ca4227 line, and gave a weight of 1 to each of the other features. Then, as an illustrative example, we used our SSP models with a bimodal IMF to fit NGC 4472 at 5′. In Table 6, we summarize the best fits obtained with these merit functions, showing that the required metallicities, ages, and IMF slopes vary little among the cases except for case D, for which, e.g., the metallicity obtained is much lower than for the others. The fact that the merit worsens considerably when combining Fe with other indices, and the fact that in case D, where we excluded all the indices except the iron lines, a fit is obtained that is not better than in case A (in which we kept most of the indices) encourages us to use case A throughout this paper. From this exercise we can conclude that the iron lines yield worse fits and that these indices should not be used in combined fits with either colors or other indices, indicating that in this set of early-type galaxies the iron is in fact deficient. Another conclusion is that the global metallicity inferred must depend upon whether we use magnesium or iron lines as the primary indicators. This result also shows how important it is to use colors and line strengths together, since in this case the number of constraints is much higher than if we use colors alone.

### 3.2. Fitting with the Chemical Evolutionary Model

Using (V − K)-Mg band and (U − V)-Hβ diagrams, we found in Paper I that for a closed box approximation these metal-rich galaxies cannot be fitted with a single IMF that is constant in time using the full chemical evolutionary model. The reason for this is the impossibility of producing a dominant old but metal-rich population in our observed galaxies. The same result was found by Casuso et al. (1996) on the basis of the Mg index. To solve this problem, we proposed a scenario invoking an IMF skewed toward high-mass stars during a short initial period $t_\text{ini}$ (<1 Gyr), followed by preferential low-mass star formation during the remaining time. In that paper the favored level of metallicity reached after this short period was ~2 Z☉ for fitting the inner regions of the three galaxies. We will use here only the bimodal IMF, since we showed in § 3.1.4 that this works slightly better than the unimodal IMF for a unique SSP.

### TABLE 5

**Weights of the Merit Function**

| COLOR/INDEX | A | B | C | D | E |
|-------------|---|---|---|---|---|
| $U - V$      | 1 | 1 | 1 | 1 |
| $B - V$      | 1 | 1 | 1 | 1 |
| $V - R$      | 1 | 1 | 1 | 1 |
| $V - I$      | 1 | 1 | 1 | 1 |
| $V - J$      | 1 | 1 | 1 | 1 |
| $V - K$      | 1 | 1 | 1 | 1 |
| CN$_1$       | 0.70 | 0.70 | 0.70 | 0 | 0.70 |
| CN$_2$       | 0.70 | 0.70 | 0.70 | 0 | 0.70 |
| Ca4227       | 0 | 0 | 0 | 0 |
| G band       | 1 | 1 | 1 | 1 |
| Fe4383       | 0 | 0.43 | 0.43 | 0.43 | 0 |
| Hβ           | 1 | 1 | 1 | 1 |
| Fe5015       | 0 | 0.43 | 0.43 | 0.43 | 0 |
| Mg$_1$       | 1 | 1 | 0 | 0 |
| Mg$_2$       | 1 | 1 | 0 | 0 |
| Mg b         | 1 | 1 | 0 | 0 |
| Fe5270       | 0 | 0.43 | 0.43 | 0.43 | 0 |
| Fe5335       | 0 | 0.43 | 0.43 | 0.43 | 0 |
| Fe5406       | 0 | 0.43 | 0.43 | 0.43 | 0 |
| Fe5709       | 0 | 0.43 | 0.43 | 0.43 | 0 |
| Fe5782       | 0 | 0.43 | 0.43 | 0.43 | 0 |
| Na D         | 1 | 1 | 1 | 0 |
| TiO$_2$      | 1 | 1 | 1 | 0 |

Notes.—Five different cases for the assignment of the weights of the merit function. Case A is the distribution used throughout this paper.

### TABLE 6

**Best Fits for NGC 4472 (5′)**

| Case | Z   | Age (Gyr) | $\mu$ | Merit |
|------|-----|-----------|-------|-------|
| A    | 0.04 | 10        | 2.3   | 16.4  |
| B    | 0.03 | 14        | 2.3   | 30.9  |
| C    | 0.04 | 8         | 2.3   | 37.1  |
| D    | 0.016 | 12   | 2.3   | 17.8  |
| E    | 0.05 | 8         | 2.3   | 17.8  |

Notes.—The best merit values obtained for NGC 4472 at 5′ using the different weight distributions listed in Table 5. Case A is used throughout this paper. We used here our SSP models with a bimodal IMF.
Fig. 14.—Merit values obtained for NGC 3379 with our SSP models in the ($\mu$, age) parameter space for different metallicities and using a unimodal IMF. The contours are separated by steps of 1.0 from 10.0 to a maximum of 25.0. In the gray scale, black indicates merits of 10.0 or lower, while merits of 25.0 or higher are white. The estimated highest acceptable merit is 10.0 (calculated on the basis of the observational errors, as explained in §3.1.4).
Fig. 15.—Same as Fig. 14, but using a bimodal IMF. Note that the fits are better than those obtained with a unimodal IMF.
Fig. 16.—Same as Fig. 15, but for NGC 4472
Fig. 17.—Same as Fig. 15, but for NGC 4594
model. This was also shown in Paper I for the evolutionary model for a limited set of indices.

3.2.1. Best Fits

Once again we work with our merit function to account for the whole set of colors and line strengths contained in the observed data. The parameter space to be scanned is therefore bounded by the values proposed in Table 8 of Paper I for the pairs \((v, \mu_0)\) that drive the gas to higher than solar metallicity at \(t_0\). However, since in the present paper we not only want to fit the three galaxies at 5° but also at 15°, it is also required to use the pairs of parameters that drive the metallicity to solar after the initial period, as was in fact shown in § 3.1.6 using the SSP models. We scanned this initial period of time with values of 0.2, 0.5, and 1 Gyr. Finally, we chose to scan the remaining IMF slope \(\mu\) between 1.3 and 2.3, while the age of the galaxy was varied from 1 to 17 Gyr.

To illustrate our best fits, in Figures 18, 19, and 20 we have presented those merit figures using the weights of case A (see § 3.1.6) that are lower than 2.5\(M_{\text{max}}\) (25.0) for \(t_0 = 0.2\) Gyr. For the sake of brevity we did not plot here the cases for \(t_0 = 0.5\) and 1 Gyr because, even if they show better fits than those in Figures 14–17, they are in general slightly worse than those obtained with 0.2 Gyr. For this reason we concentrate on this latter value for the initial period. We point out that both the final metallicity and the average metallicity are now nonfree input parameters, as in SSP models, because they depend upon the selected \(t_0, v, \mu_0, \mu_t\) and the age of the galaxy, which determine the followed chemical evolution. We also point out that in these plots we selected the pairs \((v, \mu_0)\) to drive the metallicity to \(\sim 2Z_\odot\) at \(t_0\) except for the last two rows of merit diagrams of each figure, in which the metallicity rises only to values around solar at \(t_0\). However, different chemical evolutions could be achieved by varying \(\mu\) and the age of the galaxy, driving the metallicity to values different from those obtained at \(t_0\). For example, if we make the IMF slope low and the age high, the metallicity continues to rise (for details, see Paper I).

A general trend that can be found by looking at Figures 18–20 is that acceptable fits for the three galaxies are in fact possible. Also, one can note that the gray levels are now darker than in Figures 14–17, indicating lower merits and hence better fits than those obtained with SSP models. We see that the prediction of high ages for this set of galaxies is now robust. In fact, ages above \(\sim 10\) Gyr are preferred to match the data. We also see that to fit the three galaxies we require values of \(\mu\) in the second phase always greater than \(\sim 1.7\), indicating that after the first rapid formation the formed stars were primarily of lower mass than in the solar neighborhood (\(\mu = 1.35\)). Solutions involving \(\mu < 1.35\) for the second period are not acceptable, because then we cannot stabilize the chemical evolution, which continues raising the metallicity to higher values (even higher than \(Z = 0.1\)). All this shows that low-mass stars are very important in these kinds of systems, as was pointed out by, e.g., Faber & French (1980).

Another general conclusion is that we require the star formation rate (SFR) coefficient \(v\) to be in the range \(2.5 \times 10^{-4} \text{ Gyr}^{-1} \leq v \leq 30 \times 10^{-4} \text{ Gyr}^{-1}\) (with low \(t_0\)), meaning that our values are high compared with the solar neighborhood, estimated to be \(\sim 1.92 \times 10^{-4} \text{ Myr}^{-1}\) by Arimoto & Yoshii (1986), but much lower than the values proposed by these authors in their second paper (Arimoto & Yoshii 1987) to fit the elliptical galaxies (\(\sim 96 \times 10^{-4} \text{ Myr}^{-1}\)). The reason for this difference is that they stopped the star formation after the occurrence of the galactic winds, i.e., after 1 Gyr of their model. In our study such high values do not emerge, because we do not stop the star formation (unless all the gas has been consumed, precisely when using such high values of \(v\) with normal or even higher IMF slope), and therefore unacceptable values for the metallicity of the remaining gas are obtained. This happens especially when working at low IMF slopes. This difference in input physics has important consequences for the fits obtained, since models that stop the star formation after a short initial period of time only allow the formation of stars with a mixture of metallicities, but never with a mixture of ages. We also differ from Arimoto & Yoshii (1987) in the prediction of the slope of the IMF, which they assumed to be \(\sim 1.0\) (slightly lower than Salpeter). To compare our results with theirs, we have to look at the results obtained with the unimodal IMF. The prediction that we obtained in Paper I (as can be deduced from Fig. 20 of that paper) is \(\sim 1.7\), higher than Salpeter and than their estimate. We attribute this difference to the fact that they need this combination of lower than Salpeter IMF and very high star formation rates to yield the required high metallicities in their period previous to the occurrence of the galactic wind (1 Gyr), while we obtain this in a shorter time by means of lower IMF slopes than they require. Bressan, Chiosi, & Fagotto (1994) also followed the galactic-wind scheme, without changing the Salpeter IMF, but requiring a shorter period of time before the appearance of the galactic winds. These short periods of initial different behavior are in better agreement with our best fits.

Now turning our attention to the differences within galaxies and between them, we see that NGC 3379 and the bulge of the Sombrero galaxy appear to lie in the same regions of (\(\mu, \text{age}\)) parameter space for a given \((v, \mu_0)\). We also see that, for the same set of parameters \(v\) and \(\mu_0\), NGC 4472 at 5° gives better fits for ages that are greater by \(\sim 3\) Gyr than those obtained for the other two galaxies at the same distances from their centers. However, by looking at the results obtained with the SSP models and the metallicities obtained in the best fits (given in Table 7), we are biased to think that after the initial period, \(t_0\) for NGC 3379 and NGC 4594 reached lower metallicities than NGC 4472, as also was shown in Paper I. This also holds when varying the value of the IMF slope for the remaining time. The full chemo-evolutionary models also produce the same conclusion as the SSP models when fitting the observed gradients, i.e., the metallicities of the outer regions are lower for NGC 3379 and NGC 4594 but not noticeably lower for NGC 4472, probably because the latter is too large and therefore the radial separation of the observed points does not represent an important fraction of its effective radius. In fact, in Figures 18 and 20 we see that the outer regions of NGC 3379 and NGC 4594 are only fitted in an acceptable way for the last two rows of merit figures, where the metallicity does not rise above solar at \(t_0\). For more details about the final and average metallicities, see Table 8, where we summarize the most representative fits. We also point out that in this table, comparing the \(B-V\) and \(V-K\) colors of NGC 3379 and the Sombrero galaxy, we are inclined to think that the latter could be affected by a small amount of dust, since its colors are too red while the lines seem to be well fitted. We think it likely that a reddening correction of
Fig. 18.—Merit function values in ($\mu$, age)-space obtained with our full chemo-evolutionary population synthesis model using a bimodal IMF. The initial period during which the IMF was skewed toward massive stars was 0.2 Gyr. Models for various parameters ($v', \mu_0$) (taken according to Table 8 of Paper I) are selected. The pairs ($v', \mu_0$) of the first six rows of merit diagrams drive the metallicity to $\sim 2 Z_\odot$ at $t_\odot$, while the pairs corresponding to the last two rows drive the metallicity to solar at $t_\odot$. The contours and the gray scale have been defined using the same criterion as in Figs. 14–17. Note that the fits are better, since the gray scales are now darker and occupy wider regions of the parameter space.
Fig. 19.—Same as Fig. 18, but for NGC 4472
Fig. 20.—Same as Fig. 18, but for NGC 4594


| COLOR/INDEX | ERROR | Observed | Fit | Residual |
|-------------|-------|----------|-----|----------|
| U - V        | 0.08  | 1.70     | 1.74| 0.04     |
| B - V        | 0.07  | 1.01     | 1.04| 0.03     |
| V - K        | 0.08  | 0.62     | 0.62| 0.00     |
| V - J        | 0.09  | 1.27     |     |          |
| V - R        | 0.09  | 2.35     | 2.43| 0.08     |
| V - K        | 0.10  | 3.26     | 3.37| 0.11     |
| CN1          | 0.01  | 0.09     | 0.07| -0.02    |
| CN2          | 0.01  | 0.10     | 0.10| 0.00     |
| G band       | 0.25  | 5.23     | 5.92| 0.69     |
| Hβ           | 0.17  | 1.47     | 1.26| -0.22    |
| Mg1          | 0.00  | 0.15     | 0.14| -0.01    |
| Mg2          | 0.00  | 0.30     | 0.30| 0.00     |
| Mg b         | 0.18  | 4.49     | 4.40| -0.09    |
| Na D         | 0.23  | 4.49     | 4.22| -0.27    |
| TiO          | 0.00  | 0.04     | 0.05| 0.00     |
| Ca4227       | 0.19  | 0.76     | 0.72| 1.16     |
| Fe4383       | 0.38  | 5.08     | 5.67| 1.16     |
| Fe5015       | 0.41  | 4.82     | 5.98| 1.16     |
| Fe5270       | 0.20  | 2.87     | 3.41| 0.53     |
| Fe5335       | 0.21  | 2.35     | 3.19| 0.83     |
| Fe5406       | 0.14  | 1.53     | 2.08| 0.56     |
| Fe5789       | 0.13  | 0.68     | 1.10| 0.43     |
| Fe5882       | 0.16  | 0.59     | 0.96| 0.37     |
| Ca4455       | 0.22  | 1.95     |     |          |
| Fe4531       | 0.37  | 3.95     |     |          |
| Fe4668       | 0.37  | 6.32     |     |          |
| TiO          | 0.08  | 0.03     |     |          |
| Ca1          | 0.01  | 0.18     |     |          |
| Ca2          | 0.02  | 0.47     |     |          |
| Mg1          | 0.09  | 0.91     |     |          |
| Mg2          | 0.13  | 0.77     |     |          |
| (M/L)         | 0.55  | 6.58     |     |          |

| Notes.--The fits were obtained using a bimodal IMF, for which we indicate the metallicity, the slope, and the assumed age in gigayears. We also have indicated the typical observational errors (excluding only the error that comes from the conversion to the expanded Lick system) for our measurements, to be compared with the given residuals to obtain an idea of the goodness of the fits. The Ca and Fe lines Ca4227–Fe5782 are not well fitted. The obtained merits are given in the last row, while in the previous row we note the predicted mass-to-luminosity relation. |
### TABLE 8
Representative Fits for Full Chemo-evolutionary Model

| Color/ Index | Error | Observed | Fit | Residual |
|--------------|-------|----------|-----|----------|
| U-V          | 0.08  | 1.70     | 1.62| -0.08    |
| B-V          | 0.07  | 1.01     | 1.01| 0.00     |
| V-R          | 0.08  | 0.62     | 0.62| 0.00     |
| V-I          | 0.09  | 0.12     | 1.26| 0.12     |
| V-J          | 0.09  | 2.35     | 2.43| 0.08     |
| V-K          | 0.10  | 3.26     | 3.38| 0.12     |
| CN           | 0.01  | 0.09     | 0.06| -0.03    |
| CN2          | 0.01  | 0.10     | 0.11| 0.00     |
| G band       | 0.25  | 5.23     | 5.23| 0.00     |
| Hβ           | 0.17  | 1.47     | 1.48| 0.01     |
| Mg           | 0.00  | 0.15     | 0.15| 0.00     |
| Mg2          | 0.00  | 0.30     | 0.30| 0.00     |
| MgB          | 0.18  | 4.49     | 4.40| -0.10    |
| NaD          | 0.23  | 4.49     | 4.50| 0.01     |
| TiO          | 0.00  | 0.04     | 0.05| 0.00     |
| CaII         | 0.19  | 0.76     | 1.82| 1.06     |
| Fe4383       | 0.38  | 5.08     | 6.33| 1.25     |
| Fe5015       | 0.41  | 4.82     | 5.97| 1.15     |
| Fe5270       | 0.20  | 2.87     | 3.39| 0.52     |
| Fe5335       | 0.21  | 2.35     | 3.31| 0.96     |
| Fe5406       | 0.13  | 1.53     | 2.15| 0.62     |
| Fe5709       | 0.13  | 0.68     | 1.15| 0.48     |
| Fe5782       | 0.16  | 0.59     | 0.99| 0.40     |
| CaII (1)     | 0.88  | 1.88     | 1.64| 0.18     |
| Fe4531       | 0.31  | 3.81     | 3.46| 0.63     |
| Fe4668       | 0.78  | 6.84     | 4.80| 3.84     |
| TiO2         | 0.08  | 0.08     | 0.06| 0.00     |
| Ca (1)       | 1.30  | 1.73     | 1.37| 0.40     |
| Ca (2)       | 4.36  | 4.37     | 4.37| 0.68     |
| Ca (3)       | 3.55  | 3.62     | 3.61| 0.50     |
| Mg1          | 0.97  | 0.81     | 1.00| 0.00     |
| M/Ly         | 4.42  | 5.44     | 5.44| 0.00     |
| Zsolar       | 0.0469| 0.0468   | 0.0463| 0.00    |
| Z         | 0.0426| 0.0188   | 0.0472| 0.00   |
| Merit        | 9.27  | 16.19    | 10.90| 9.61    |

**Notes:** The fits were obtained under the assumption of a variable IMF scenario, with a bimodal IMF. The SFR coefficient is in units of $10^{-4}$ Myr$^{-1}$ while $t_0$ and the age of the galaxy are in units of gigayears. We have also indicated the typical observational errors for our measurements, to be compared with the given residuals to obtain an idea of the goodness of the fits. The Ca and Fe lines Ca4227–Fe5782 are not well fitted. Z$_{rel}$ denotes the metallicity obtained by the given chemical evolution model at the present time, while $\langle Z \rangle$ is the average metallicity obtained. Note that $\langle Z \rangle$ was ~ 2 times solar for the three galaxies at 5°, while for NGC 3379 and NGC 4594 at 15° it was around solar.
Fig. 21.—Chemical and fractional gas mass evolution and the predicted distributions of the live stars as a function of the metallicity, time, and temperature for different broadband filters in a representative solution for NGC 3379 at 5′. This fit was obtained for $t_0 = 0.2$ Gyr, $\mu_0 = 0.8$, $\nu = 30$, $\mu = 2.3$, and assuming an age of 15 Gyr. The quantity $L_{rel}$ represents the fraction of the total luminosity.

$E(B - V) \sim 0.05$ should be applied. However, the improvement in our fit will not be very large, given the size of the error bars.

Finally, in Figures 21 and 22 we show the chemical and fractional gas mass evolution as well as the distribution of the live stars as a function of metallicity, age, and temperature for the two selected positions of NGC 3379. We see that at 5′ the stars mainly have metallicities higher than solar (weighting in the $V$ band), but with approximately 20% of the light coming from stars with metallicity of solar or lower. However, at 15′ we see that most of the stars (around 90%) have solar metallicity. From the diagrams giving the predicted distributions of stars as functions of time, one can also note that the bulk of the stars were formed at an early stage of the evolution of the galaxy, at ages lower than some $\sim 1.5$ Gyr. In general, for the three galaxies we find that the contribution to the light in the $U$ band is around $\sim 30\%$ for giants and $\sim 70\%$ for dwarfs, in the $V$ band it is $\sim 50\%$ for giants and $\sim 50\%$ for dwarfs, while in the $K$ band the proportions are $\sim 75\%$ for giants and $\sim 25\%$ for dwarfs.

3.3. **SSP Models versus Chemical Evolutionary Models**

We find that, using the evolutionary model, most of the stars were formed in the early stages ($<1.5$ Gyr) of the galactic evolution, as seen in Figures 21 and 22. Therefore it is not surprising that, qualitatively, the fits from the evolutionary model are not very different from those of the single-age, single-metallicity models. Somewhat better fits are obtained, however, indicating that these galaxies probably have stars with a mixture of metallicities, as has been found also in our Galactic bulge (Rich 1988).

It is also easy to understand that the evolutionary model yields somewhat larger ages, since stars of lower metallicities have to be compensated for by giving the whole population a greater age.
4. CONCLUSIONS

We have obtained high-quality observations of almost the whole set of line indices of the extended Lick system for three representative early-type galaxies and have applied a new spectrophotometric chemo-evolutionary population synthesis model developed by ourselves in a previous paper (Paper I).

We can make models that yield good fits in all the colors and many of the most important line indices. These fits, however, cannot synthesize quantitatively a number of lines, primarily from Fe and Ca. We find that six independent Fe lines are too weak compared with lines of all other elements, indicating that the iron abundance is anomalous and deficient in the radial range of the galaxies that we studied. This implies that the global metallicity inferred must depend upon whether we use magnesium or iron lines as the primary indicators. By invoking ß-enhancement one can obtain better fits for the iron lines, but other features such as Na D then become worse if we follow the abundance ratios given in Weiss et al. (1995). Finally, we find that the Ca4227 index is much fainter than predicted by the models.

In general, we find that the three galaxies require metallicities higher than solar for the inner regions while the ages are older than 10 Gyr, and the observed radial gradients are due to metallicity decreasing outward. We also find that NGC 4472 is more metal rich than the other two galaxies.

To fit this set of galaxies with the full chemical evolutionary population synthesis model, we used the variable IMF scenario (defined in Paper I), which invokes an IMF skewed toward high-mass stars in the beginning, during a short period of time (<1 Gyr), and toward low-mass stars later for the remaining time. The best fits indicate that dwarfs contribute ~70% to the U band, ~50% in V, and ~25% in K.

We find that slightly better fits are obtained with the chemo-evolutionary model than with the single-age, single-metallicity model, justifying the extra complications. However, since the predicted spread in metallicities is not very large and since the bulk of the stars were formed at very early stages of the galactic evolution (at ages lower...
than \( \sim 1.5 \) Gyr), we conclude that the single-age, single-metallicity stellar population models offer reasonable first-order fits to these kinds of stellar systems, especially if one wishes to avoid computational complexity.

This study shows that it would be useful to extend the present analysis to include other features at shorter wavelengths in the UV region, such as the indices of Rose (1994), and to the near-IR with indices such as Na I at 8190 Å, the Ca II triplet, and the CO or H2 features. To understand the stellar populations of the early-type galaxies and to, e.g., disentangle age and metallicity (Jones & Worthey 1995; Bressan, Chiosi, & Tantalo 1996), it will be important to introduce as many constraints as possible, by observing the galaxies in many calibrated absorption lines.

The observational data presented in this paper are available in computer-readable form in the AAS CD-ROM Series, Volume 8.

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