

An interpretation of the line-strength indices in old stellar populations using an evolutionary synthesis approach

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Summary. Evolutionary population synthesis models with different metallicities have been computed in order to interpret the observed Mg_2 and $H\beta$, line-strength indices in old stellar populations. Both indices are found to be quite insensitive to changes in the slope of the IMF and the upper mass limit. These models have been applied to three different cases, with the following results:

a) Galactic globular clusters do not exhibit a significant dispersion in age, and the metallicities of the computed models resemble those estimated for the clusters. The indices for the metal-poor globulars ($[Fe/H] < -1$) cannot be attained with these models due to the lack of low metallicity evolutionary tracks and stellar spectra libraries.

b) The line-strength gradients observed in the elliptical galaxy NGC 5813 are due, essentially, to intrinsic variations in metallicity, and they cannot be explained just from changes in the remaining parameters of the stellar population.

c) In order to synthesize the M 32 indices we must introduce a star formation elapsed for a long time-scale, the star formation being still significant $\simeq 5$ Gyr ago.

Key words: galaxies: stellar content of – galaxies: elliptical – galaxies: metallicity gradients – clusters: globulars

1. Introduction

Recent studies have led to the conclusion that the stellar populations in the stellar systems considered classically as old (i.e. globular clusters, elliptical galaxies), do not represent a one parameter family (see Burstein, 1985 for a review). In particular, Burstein et al. (1984) analysis of the line-strength indices in galactic globular clusters, M 31 globular clusters and the nuclei of elliptical galaxies supports the evidence that those stellar populations must differ in some parameter other than the mean metallicity.

Among the line-strength indices defined by Burstein et al. (1984) we have focused our attention on the Mg_2 and $H\beta$ indices. The former measures the intensity of the Mg “b” triplet and the MgH band around 5175 Å, and it has been used as a metallicity indicator by several authors (e.g. Mould 1979, Burstein 1979, Efstathiou and Gorgas, 1985). On the other hand, $H\beta$ should be

sensitive to the age of the populations, since its strength can be a measure of the number of young stars present in the population. The properties of these indices make the $H\beta - Mg_2$ diagram a useful tool for the analysis of intrinsic differences among stellar populations, i.e. differences in age and metallicity. In fact, Burstein et al. (1984) have noted that the nuclei of ellipticals exhibit an enhanced $H\beta$ index when compared with galactic globular clusters at a fixed Mg_2 value. Gunn et al. (1981) suggest that this fact is indicative of a modest rate of current star formation. On the other hand, different authors (O’Connell, 1980; Pickles 1985b; Rose 1985) favour the presence of an intermediate age stellar population.

The interpretation of the line-strengths in composite stellar populations in terms of physical parameters such as age or metallicity is a complex problem that has been previously challenged by several authors (Faber, 1972; Mould, 1979 and others). A proper study of this question must rest on population synthesis methods.

Classically the population models have followed a static method (Faber, 1972; O’Connell, 1976, 1980; Pickles, 1985b; Pritchett, 1977; Turnrose, 1976), in which the number of stars of each type present in the system (e.g. galaxy) was determined minimizing the differences of the composite spectrum with the observed one. Though this method has been useful to trace down the distribution in mass and luminosity of the stars, it has left a number of problems unsolved (see Pickles, 1987). On the other hand, a more straightforward approach to the problem of composite stellar populations could be made using evolutionary population synthesis models (as those of Tinsley, 1980 and Bruzual, 1983) which can provide directly the main parameters of the population. The main problems for the application of this method arise basically from the large uncertainties in the knowledge of the stellar evolution, and also in the lack of stellar spectra libraries of different metallicities.

In this paper we have used this evolutionary synthesis approach in order to study the line-strength indices of several stellar populations. In Sect. 2 we describe how we have dealt with the problems noted above. In Sect. 3, the line-strength indices of galactic globular clusters are synthesized using the method. In the same way, we have interpreted the line-strength gradient measured in elliptical galaxies, using the data for NGC 5813 from Efstathiou and Gorgas (1985). The low metallicity ellipticals are good candidates for been studied following this method. In this sense we analyze the line-strengths in the well-known galaxy M 32.

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2. The synthesis

The population synthesis models build up by us, follow essentially the procedure described by Tinsley (1980) and Bruzual (1983). The models were performed using a star formation rate (SFR), an initial mass function (IMF), a set of evolutionary tracks for different stellar masses and a library of stellar spectra covering as fully as possible all the spectral types and luminosity classes. This allows us to synthesize the spectrum and, therefore, the indices for a stellar population of any age.

The stellar formation history of the population was mimicked considering the constant, exponential and delayed SFR, introduced by Bruzual and Kron (1980) and Bruzual (1983), and the IMF given by Miller and Scalo (1979). The models were computed assuming a mass ranging between $m_s = 0.07 M_\odot$ and $m_u = 75 M_\odot$ for the born stars. In order to obtain a realistic mass-to-light ratio we also included objects with masses from $m_l = 0.05 M_\odot$ to m_s , which do not become luminous stars in the whole life of the system (Bruzual, 1983).

The evolutionary tracks corresponding to different mass ranges were collected from several authors. We have assumed that stars with $M < 0.7 M_\odot$ do not leave the main sequence in time-scales comparable to the age of the population. A dense set of detailed tracks was chosen for intermediate masses ($0.8 M_\odot < M < 2 M_\odot$) which have a significant effect on the indices. For the high mass range ($M > 10 M_\odot$) tracks computed with intermediate mass loss were used (Maeder, 1981a,b). The sources of the evolutionary tracks are listed in Table 1.

We have taken the stellar library published by Pickles (1985a) and several giant and supergiant spectra from Jacoby et al. (1984). The Mg_2 and $H\beta$ line-strength indices were measured in these spectra. Both are well correlated with effective temperature, Mg_2 increasing up to 0.5 mag for M stars. The K giant spectra analysis from Faber et al. (1985) shows that Mg_2 is also sensitive to metallicity and surface gravity, and $H\beta$ is likely to depend on gravity but not on metallicity. The indices measured in this work confirm these trends.

With these ingredients we have synthesized a set of population models with five different metallicities, obtaining composite spectra in which the Mg_2 and $H\beta$ indices were measured. Figures 1(a), (b) show the evolution with time (from 3 to 18 Gyr) of Mg_2 and $H\beta$ for the models computed with solar metallicity, an exponential SFR and τ parameters 0.5, 1 and 5 Gyr. In all cases,

Mg_2 increases and $H\beta$ decreases as the population gets older. An opposite trend is observed when the stellar formation is elapsed during longer time-scales (larger τ). These models also confirm that for ages > 10 Gyr (except for very high values of τ) the number of MS low mass stars is dominant. When the SFR is exponential or delayed, some star formation remains and high mass stars have a significant contribution to the luminosity. We also find that there is an important contribution ($\approx 50\%$) to the V light from subgiants and G – K dwarfs, in agreement with Pickles (1985b) and Rose (1985). If the SFR is constant, the number of blue stars is negligible.

In order to study the chemical composition effect on the synthesized indices, we have computed models with evolutionary tracks of high metal content ($[Fe/H] \approx 0.6$). The main difficulty arises from the small number of metal-rich stars in the libraries, since only G and K giants with $0.2 < [Fe/H] < 0.40$ are available from Pickles compilation. Therefore, we are restricted to use solar metallicity stars, except for those types. However this difficulty can be weakened by using non-solar metallicity evolutionary tracks. Actually, a rise in the metal content leads to a shift in the track of a given mass to lower temperatures and luminosities in the HR diagram. This meaningfully changes the indices as the assigned spectrum for each point of the tracks correspond to a cooler and fainter star. Our analysis shows that this should be more effective than the change in the metallicity of the library spectra.

If the remaining parameters of the synthesis are fixed, models computed with “high metallicity” lead to higher values for Mg_2 and lower for $H\beta$ than the derived with solar metallicity. Notice that, even though $H\beta$ is almost insensitive to the metallicity of a single star, it is affected when we consider the spectrum of a composite population, due to changes in temperature and luminosity.

In order to introduce a low metal content in the models we are compelled to use just low-metal giant stars ($-2.4 < [Fe/H] < -1.3$) as before. In this case, the evolutionary tracks, corresponding to $[Fe/H] = -1.0, -0.76$ and -0.46 , are shifted towards higher luminosities and effective temperatures. The results confirm the same trends of Mg_2 and $H\beta$ with metallicity as noted above.

In order to check for the effect of the upper mass limit we have computed models with $m_u = 30$ and $15 M_\odot$. No significative variations in the indices can be found for populations of ages $\gg \tau$.

Table 1. Sources of evolutionary tracks

Mass (M_\odot)	References	Composition	Comments
$0.09 \leq M \leq 0.69$	Tinsley and Gunn, 1976	Solar	Non-evolving
$0.8 \leq M \leq 1.85$	VandenBerg, 1985	($Y = 0.25, Z = 0.0169$)	
$0.8 \leq M \leq 1.85$	VandenBerg, 1985	($Y = 0.25, Z = 0.006$)	
$0.8 \leq M \leq 1.85$	VandenBerg, 1985	($Y = 0.25, Z = 0.003$)	
$0.8 \leq M \leq 1.85$	VandenBerg, 1985	($Y = 0.25, Z = 0.0017$)	
$2 \leq M \leq 7$	Alcock and Paczyński, 1978	($X = 0.70, Z = 0.03$)	
$2 \leq M \leq 7$	Alcock and Paczyński, 1978	($X = 0.70, Z = 0.01$)	
$2 \leq M \leq 7$	Alcock and Paczyński, 1978	($X = 0.70, Z = 0.003$)	
$2 \leq M \leq 7$	Alcock and Paczyński, 1978	($X = 0.70, Z = 0.001$)	
$0.7 \leq M \leq 5.50$	Mengel et al., 1979	($Y = 0.30, Z = 0.1$)	
$9 \leq M \leq 30$	Maeder, 1981b	($X = 0.70, Z = 0.02$)	Intermediate mass loss (case B)
60	Maeder, 1981a	($X = 0.70, Z = 0.02$)	Intermediate mass loss (case B)

end

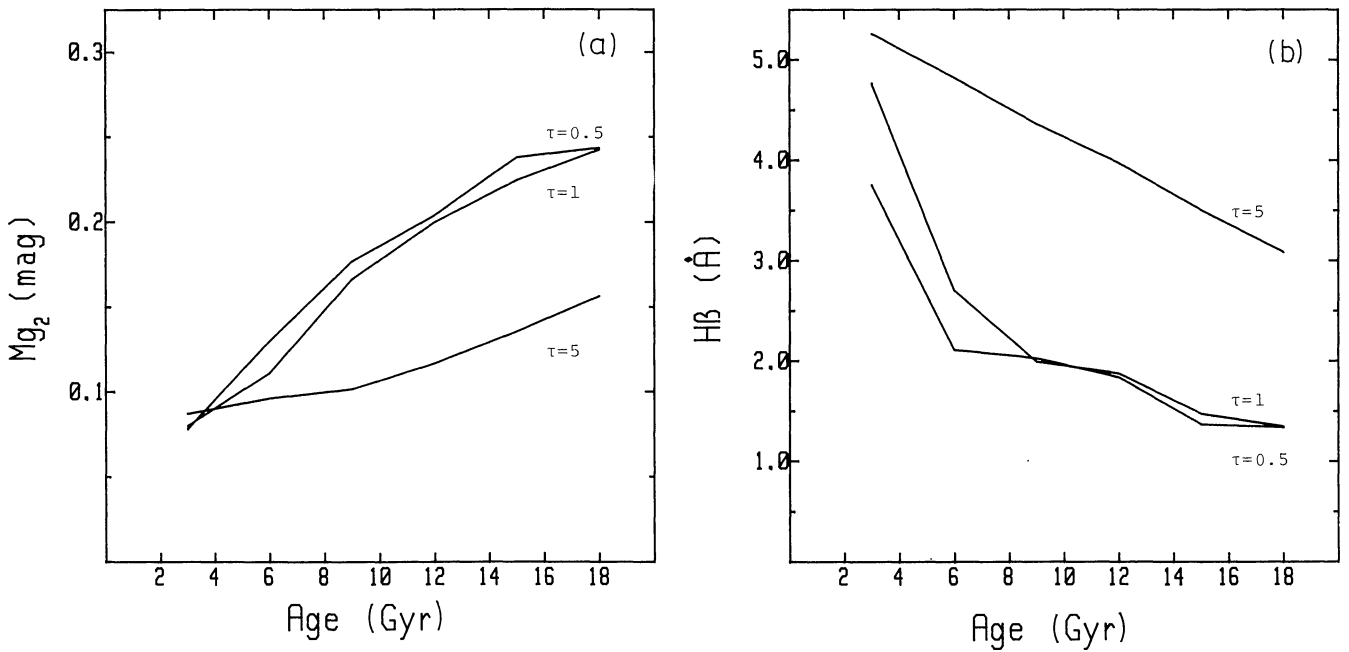


Fig. 1a. Evolution with time of the Mg_2 index in steps of 3 Gyr from models computed with solar metallicity, exponential SFR, Miller and Scalo (1979) IMF and τ values of 0.5, 1 and 5 Gyr. **b** Same as **a** for $H\beta$

For these ages, stars of high masses have almost disappeared, and their effect in the indices is negligible.

To study the IMF effect on the results, changes from 0.50 to 1.50 in the slope have been introduced, observing variations of roughly 0.035 mag in Mg_2 and 0.2 \AA in $H\beta$. These small variations agree with the results obtained by Faber (1972) and Mould (1978) for their Mg indices. This can be interpreted taking into account that even though a change in the IMF slope changes the ratio between giant and dwarf stars, the Mg_2 and $H\beta$ indices are not enough gravity sensitive to discriminate strongly between the values of the slope (Mould, 1978).

4. Discussion

The above results allow us to interpret, at least in a qualitative way, the line-strength indices $H\beta$ and Mg_2 in old stellar populations. We have tried to explain the behaviour of the indices in three different situations: the differences in the indices among galactic globular clusters, the line-strength gradient within a galaxy and the indices for the central part of different galaxies. We will discuss each case separately.

4.1. Galactic globular clusters

Evolutionary population synthesis models should be very suitable for modelling globular cluster line-strength indices. In order to achieve that we have assumed a single generation of stars, all born in a short time-scale (as compared with the age of the cluster), which involves a SFR with a small τ parameter (< 1 Gyr). For these small values of τ , the results are independent of this parameter. No chemical evolution inside the cluster is needed as we consider a single generation of stars. Because of that, the position of the clusters in a $H\beta - Mg_2$ diagram should reflect changes in metallicity of the material from which they were

formed, in the age (if any), and perhaps slightly in the IMF.

The general consensus over the past five years is that the spread in age among the known galactic globular clusters is probably small, perhaps less than 1 Gyr, and that these clusters are as old as the Galaxy (see Burstein, 1985, and references therein). Models with these characteristics have been computed with metallicities ranging from $[Fe/H] \simeq -1$ to solar. The computed indices agree with the values for the galactic globular clusters studied by Burstein et al. (1984), whose metallicities have been estimated by Zinn and West (1984).

Figure 2 displays an $H\beta$ versus Mg_2 diagram in which the points represent the indices measured by Burstein et al. (1984) for their sample of galactic globular clusters. Different symbols refer to different metallicity bins, according to the values given by Zinn and West (1984). The uncertainties in $[Fe/H]$ are typically from 0.1 to 0.2 dex. The computed indices corresponding to each metallicity with different age are shown. Each line represents the evolution of the indices with time in steps of 3 Gyr and up to 15 Gyr, labelled according to the metallicity of the tracks. The points at the end of the lines lie well within the area corresponding to globular clusters with metallicities > -1 . Differences on these indices from cluster to cluster are likely to be due to metallicity variations. No significant spread in age can be deduced from our models.

In the $H\beta - Mg_2$ diagram the M 31 globular clusters studied by Burstein et al. (1984) exhibit, at a given Mg_2 , stronger $H\beta$ line-strengths than the galactic globular clusters. Our model results agree with Burstein (1985) conclusions that a substantial difference in age can be the source of the spectral line differences between M 31 globular clusters and the galactic globulars, the former being $\simeq 3$ Gyr younger than the latter.

We are not able to model the clusters with metallicities lower than $[Fe/H] \simeq -1$ due to the characteristics of the evolutionary tracks used in this work. A variation in the remaining parameters of the models cannot lead to such indices.

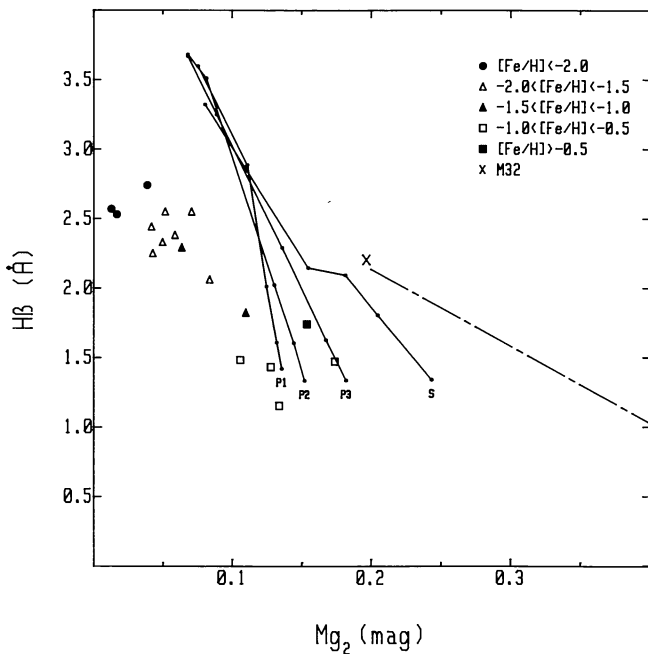


Fig. 2. $H\beta$ versus Mg_2 diagram for the galactic globular clusters. Values are from Burstein et al. (1984). Different symbols refer to different metallicity bins according to the values given by Zinn and West (1984). The dashed line is a mean relationship for the nuclei of elliptical galaxies (Burstein et al., 1984). Lines show the evolution of the indices from models computed for a single generation of stars, with Miller and Scalo (1979) IMF, for metallicities $[Fe/H] = -1$ (P1), $[Fe/H] = -0.76$ (P2), $[Fe/H] = -0.46$ (P3) and $[Fe/H] = 0$ (S). The values are computed in steps of 3 Gyrs with the last point corresponding to 15 Gyr

4.2. Line-strength gradients in NGC 5813

In Fig. 3 we show the indices measured by Efstathiou and Gorgas (1985) for the elliptical galaxy NGC 5813 at different galactocentric distances. They are plotted as crosses, with the distance to the center increasing from right to left. The evolution of the synthesized indices from 3 to 18 Gyr is shown as in Fig. 2. We plot the results for track metallicities $[Fe/H] = -1$ (mp), 0.0 (s) and $+0.6$ (mr), with an exponential SFR and an e-folding time τ of 1 Gyr. The dashed line represents the results from the solar metallicity models with an exponential SFR and $\tau = 3$ Gyr. It shows the effect of changing the star formation time scale. It can be seen that the indices for the central region can only be reached with the high metallicity models. With lower metallicities these indices cannot be attained, no matter which synthesis parameters are used. The indices of an intermediate region ($r \approx 10''$) can be reproduced with population synthesis of solar metallicity. Models with low metallicity lead to indices similar to those of further out regions, but do not reach the outer points (the tip observed in the last points of this low metallicity models is due to discontinuities between the sets of evolutionary tracks). From the results obtained with these models, it seems that we would need an even lower metallicity to reach the outer values, since no other combination of parameters can lead to lower Mg_2 indices without increasing $H\beta$. Figure 4 shows the synthetic spectra for three metallicities and, superposed, the spectra of NGC 5813 at radii $0.6''$, $8.3''$ and $47''$, with similar indices to those of the models.

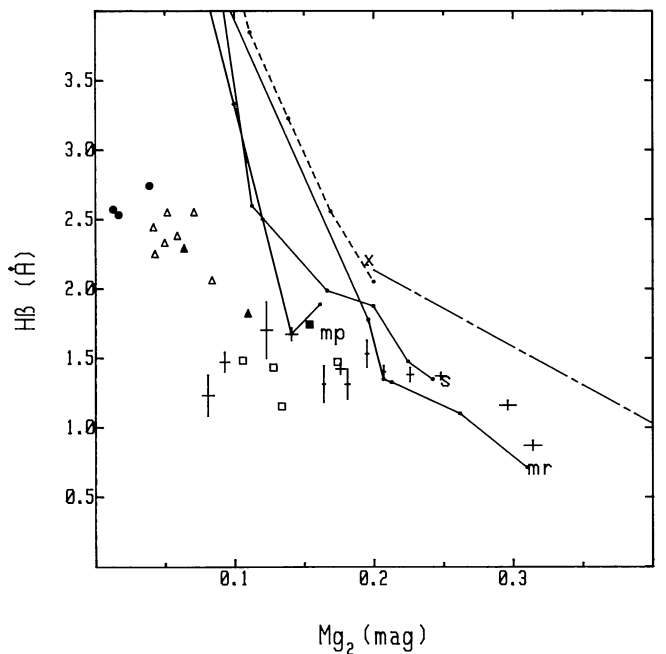


Fig. 3. $H\beta$ versus Mg_2 diagram showing the indices for NGC 5813 from Efstathiou and Gorgas (1985) (Crosses with sizes indicating 1σ errors). The position of the indices for the globulars and M 32 (X), and the mean relationship for the ellipticals are also plotted for reference. Lines show the evolution of the indices from models computed with an exponential SFR, $\tau = 1$ Gyr, Miller and Scalo (1979) IMF, for metallicities $[Fe/H] = -1.0$ (mp), $[Fe/H] = 0$ (s) and $[Fe/H] = 0.6$ (mr). The values are computed in steps of 3 Gyr, with the last point corresponding to 18 Gyr. The tip of the metal poor line is due to discontinuities between the sets of evolutionary tracks used. The dashed line represents the results from the solar metallicity models with an exponential SFR and $\tau = 3$ Gyr

The study of the indices behaviour under a continuous change in metal content is not possible at present, due to the lack of non-solar metallicity stellar spectra and evolutionary tracks covering a continuous range of metallicity. This, together with the differences between stellar and track metallicities, constrains us to a qualitative study making impossible to give numerical estimates of the actual metallicities. Anyway, it seems clear from our results that line-strength gradients are due essentially to intrinsic variations in metallicity and cannot be explained just from changes in the remaining parameters of the stellar populations, i.e. age, IMF, etc.

4.3. M 32

As a further application of our models to the understanding of the line-strength indices in galaxies we have studied the well known elliptical galaxy M 32, which has been previously studied by several authors using empirical population synthesis (Spinrad and Taylor, 1971; Faber, 1972; Williams, 1976; Pritchett, 1977; O'Connell, 1980). Only the last author has made an attempt of studying the age structure of the population. His main results are that the metallicity of M 32 is solar within ≈ 0.1 dex, and that major star formation continued until ≈ 5 Gyr ago (or ≈ 10 Gyr after the oldest galactic globular clusters were formed). However, an important amount of light could arise in a significantly older population, and the maximum of the SFR could have taken place much earlier.

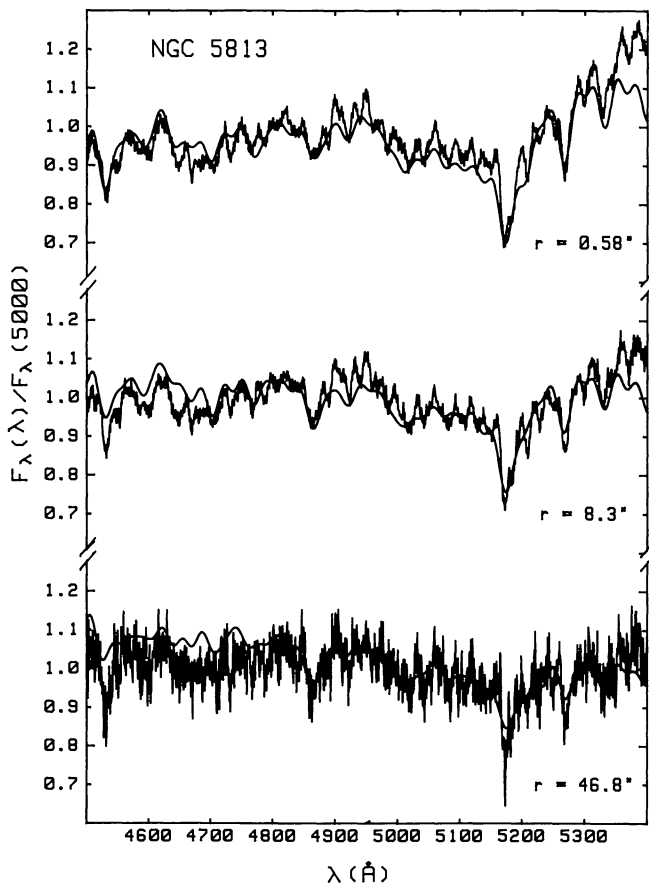


Fig. 4. Spectra of NGC 5813 (Efsthathiou and Gorgas, 1985) at different radii, and, superposed, synthetic spectra computed with exponential SFR ($\tau = 1$ Gyr), Miller and Scalo (1979) IMF, for ages of 16 Gyr and metallicities $[\text{Fe}/\text{H}] = -1, 0.0$ and 0.6 (from top to bottom)

In the $H\beta - \text{Mg}_2$ diagram (Fig. 3) M 32 lies near the edge of the plotted main relationship for elliptical nuclei, with a low Mg_2 and high $H\beta$ indices. These cannot be reproduced using models for a population intrinsically young (≈ 5 Gyr), whatever synthesis parameters we introduce. On the other hand, models for an intrinsically older population (≈ 15 Gyr) can lead to such indices when an Exponential or Delayed SFR with a τ parameter relatively large ($\tau \approx 3$ Gyr for an Exponential SFR – Fig. 3, dashed line – or $\tau \approx 2$ Gyr for a Delayed SFR) are introduced. This means that the star formation in this galaxy is likely to have taken place over a period much longer than in the above cases.

In this framework, the observed indices are consistent with a star formation which began ≈ 15 Gyr ago, and elapsed significantly over ≈ 10 Gyr. Our models also confirm that the turn-off group is near late F stars (O'Connell, 1980). This study rests upon the models computed with solar metallicity (for the evolutionary tracks and stellar spectra), thus we can be quite confident on the results since the uncertainties are smaller.

5. Concluding Remarks

From the previous works in this field (Bruzual and Kron, 1980, Bruzual 1983, Arimoto and Yoshii, 1986 and González-Riestra, 1986) and the results presented in this paper, the evolutionary population synthesis has proved to be a powerful tool for study-

ing stellar populations in very different situations. The examples we have presented here show that this technique can help to interpret the line-strengths in the integrated spectra of old stellar populations. We must stress the importance of improving the synthesis ingredients. Evolutionary tracks and, especially, stellar spectra libraries of different metallicities are hardly needed. Making efforts in the sense of elaborating more sophisticated models with improved ingredients and including chemical evolution, can provide clues for the proper interpretation of the line-strength indices in old stellar populations.

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