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SEARCHING FOR EVIDENCE OF SPECTRAL EVOLUTION OF GALAXIES

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RESUMEN

Se describe los diferentes enfoques que han sido utilizados para detectar cantidades significativas de evolución espectral al comparar galaxias equivalentes observadas en diferentes épocas cosmológicas. Se discute el papel de los modelos evolutivos de síntesis de poblaciones estelares en la interpretación de estas observaciones.

ABSTRACT

I describe several approaches that have been used to detect significant amounts of spectral evolution comparing equivalent galaxies seeing at different cosmological times. The role of evolutionary population synthesis models in the interpretation of these tests is discussed.

Key words: **GALAXIES-EVOLUTION — GALAXIES-STELLAR CONTENT**

1. INTRODUCTION

The number distribution of the stellar populations present in a galaxy is a function of time. Thus, the number of stars of a given spectral type, luminosity class, and metallicity content changes as the galaxy ages. In early-type galaxies (E/S0) most of the stars were formed during, or very early after the initial collapse of the galaxy and the stellar population ages as times goes by. The chemical abundance in these systems must have reached the value measured in the stars very quickly during the formation process since most E/S0 galaxies show little evidence of recent major events of star formation. In late-type galaxies the stellar population also ages, but there is a significant number of new stars being formed. Depending on the star formation rate, $\Psi(t)$, the mean age of the stars in a galaxy may even decrease as the galaxy gets older. In general, in late-type systems the metal content of the stars and the interstellar medium is an increasing function of time. $\Psi(t)$ can also increase above its typical value due to interactions between two or more galaxies or with the environment.

As a consequence of the aging of the stellar population, or its renewal in the case of galaxies with high $\Psi(t)$, the rest-frame spectral distribution of the light emitted by a galaxy is a function of its proper time. Observational properties such as photometric magnitude and colors, line strength indices, metal content of gas and young stars, depend on the epoch at which we observe a galaxy on its reference frame. This *intrinsic* evolution should not be mistaken with the *apparent* evolution produced by the cosmological redshift z. For distant galaxies both effects may be equally significant.

In order to search for spectral evolution in galaxy samples we must *(a)* quantify the amount of evolution expected between cosmological epoch t_1 and t_2, and *(b)* design observational tests that will reveal this amount of evolution, if present. Evolutionary population synthesis models predict the amount of evolution expected under different scenarios and allow us to judge the feasibility of measuring it. In the ideal case (Aragón-Salamanca et al. 1993; Stanford et al. 1995; Bender et al. 1996) spectral evolution is measured simply by comparing spectra of galaxies obtained in such a way that the same rest frame wavelength region is sampled in all galaxies, irrespective of z. In this case there is no need to apply uncertain K-corrections to transform all the spectra to a common wavelength scale. Alternatively, if this approach cannot be applied, e.g., when studying large samples of faint galaxies, one can use models which allow for different degrees of evolution (including none) to derive indirectly the amount of evolution consistent with the data (Pozzetti et al. 1996; Metcalfe et al. 1996). Clearly, the first approach is to be preferred whenever possible. In all cases we must rule out possible deviations from the natural or passive evolution of the stellar population in some of the galaxies under study induced, for example, by interactions with other galaxies or cluster environment, etc.

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2. EVOLUTIONARY POPULATION SYNTHESIS MODELS

A number of groups have developed in recent years different population synthesis models which provide a sound framework to investigate the problem of spectral evolution of galaxies. Some of the most commonly used models are Arimoto & Yoshii (1987), Guiderdoni & Rocca-Volmerange (1987), Buzzoni (1989), Bressan, Chiosi, & Fagotto (1994), Fritze-v.Alvensleben & Gerhard (1993), Worthey (1994), Bruzual & Charlot (1993). The basic astrophysical ingredients used in these models are: *(1)* Stellar evolutionary tracks of one or more metallicities; *(2)* Spectral libraries, either empirical or theoretical model atmospheres; *(3)* Sets of rules, or calibration tables, to transform the theoretical HR diagram to observational quantities (e.g., $B - V$ *vs.* T_{eff}, $V - K$ *vs.* T_{eff}, *B.C. vs.* T_{eff}, etc.). These rules are not necessary when theoretical model atmosphere libraries are used which are already parameterized according to T_{eff}, *log g*, and [Fe/H]; *(4)* Additional information, such as analytical fitting functions, required to compute various line strength indices (Worthey et al. 1994). Regardless of the specific computational algorithm used, all evolutionary synthesis models depend on three adjustable parametric functions: *(1)* the stellar initial mass function, $f(m)$, or IMF; *(2)* the star formation rate, $\Psi(t)$; and *(3)* the chemical enrichment law, $Z(t)$. For a given choice of $f(m)$, $\Psi(t)$, and $Z(t)$, a particular set of evolutionary synthesis models provides: *(1)* Galaxy spectral energy distribution (SED) *vs.* time, $F_\lambda(\lambda, Z(t), t)$; *(2)* Galaxy colors and magnitude vs. time; *(3)* Line strength and other spectral indices vs. time. Some authors (e.g. Bressan et al. 1994; Fritze-v.Alvensleben & Gerhard 1994) consider that $Z(t)$ can be derived self-consistently from their models. In other instances $Z(t)$ is introduced as an external piece of information (Bruzual & Charlot 1996, hereafter BC96). In the rest of this section I discuss some results from work still in progress in collaboration with S. Charlot (BC96).

3. BC96: A MULTI-Z SET OF EVOLUTIONARY SYNTHESIS MODELS

BC96 have used several sets of stellar evolutionary tracks based on the work of the *Padova School*. The tracks have been developed during the last two years by the combined effort of many authors: Chiosi, Bressan, Bertelli, Fagotto, Nasi, and others. The tracks are available for six different values of the stellar metallicity $Z = 0.0004, 0.004, 0.008, Z_\odot = 0.02, 0.05$, and 0.10, and cover all phases of stellar evolution from the main sequence to the black hole, neutron star, or white dwarf stage, for stars of mass from 0.1 to 120 $M_\odot$. Phases after the Post-AGB were added by BC96 from different sources. The stellar spectra have been obtained from the Kurucz (1992) library of stellar model atmospheres ($T_{eff} \geq 3500$ K) and the Bessel et al. (1991) models ($T_{eff} < 3500$ K) by interpolation at the corresponding Z. The second data set has been transformed to the wavelength scale of the Kurucz library by Lejeune et al. (1996).

3.1. Dependence of Galaxy Properties on Stellar Metallicity

Figure 1 shows the predicted SEDs at $t = 12$ Gyr for chemically homogeneous simple stellar populations (SSPs) of the indicated metallicity. In an SSP all the stars form at $t = 0$ and evolve passively afterward. In all the examples shown in this paper I assume that stars form according to the Salpeter (1955) IMF in the range from $m_L = 0.1$ to $m_U = 125$ $M_\odot$. The total mass of the model galaxy is 1 $M_\odot$. The SEDs shown in Fig. 1 have been normalized at $\lambda = 5500$Å to make the comparison more clear. Fig. 2. shows the evolution in time of the $B - V$ and $V - K$ colors, and the M/L_V ratio predicted by BC96 for the same SSPs shown in Fig. 1.

TABLE 1

CHEMICAL COMPOSITION

Z	X	Y	[Fe/H]
0.0004	0.7686	0.2310	−1.6464
0.0040	0.7560	0.2400	−0.6392
0.0080	0.7420	0.2500	−0.3300
0.0200	0.7000	0.2800	0.0932
0.0500	0.5980	0.3520	0.5595
0.1000	0.4250	0.4750	1.0089

From Figs. 1 and 2 it is apparent that there is a uniform tendency for galaxies to become redder in $B - V$ as the metallicity increases from $Z = 0.0004$ ($\frac{1}{50}Z_\odot$) to $Z = 0.05$ ($2.5 \times Z_\odot$). The tendency reverses at the

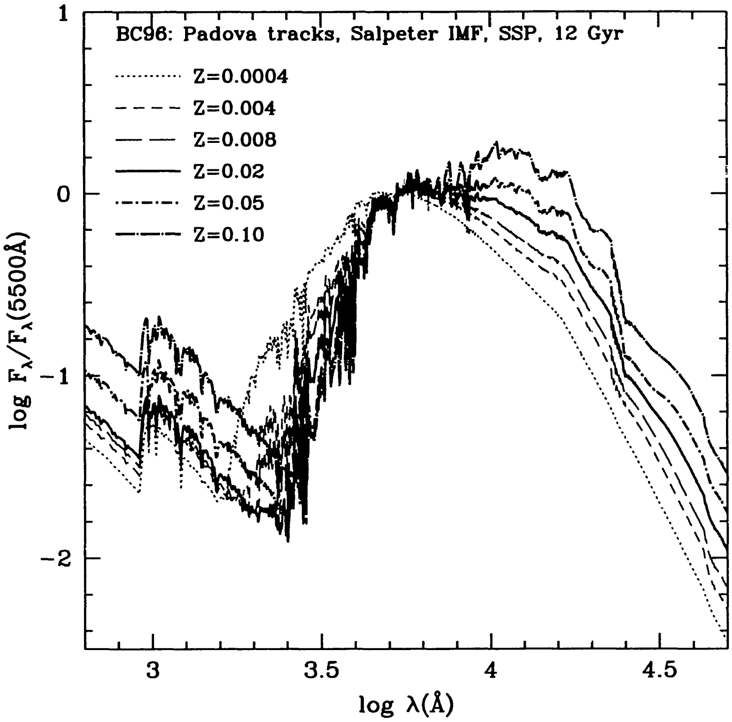

Fig. 1. Chemically homogeneous BC96 SSP model galaxy SEDs at age = 12 Gyr. Each line pattern represents a different metallicity, as indicated inside the frame. All the models shown were computed for the Salpeter (1955) IMF ($m_L = 0.15$, $m_U = 125\ M_\odot$).

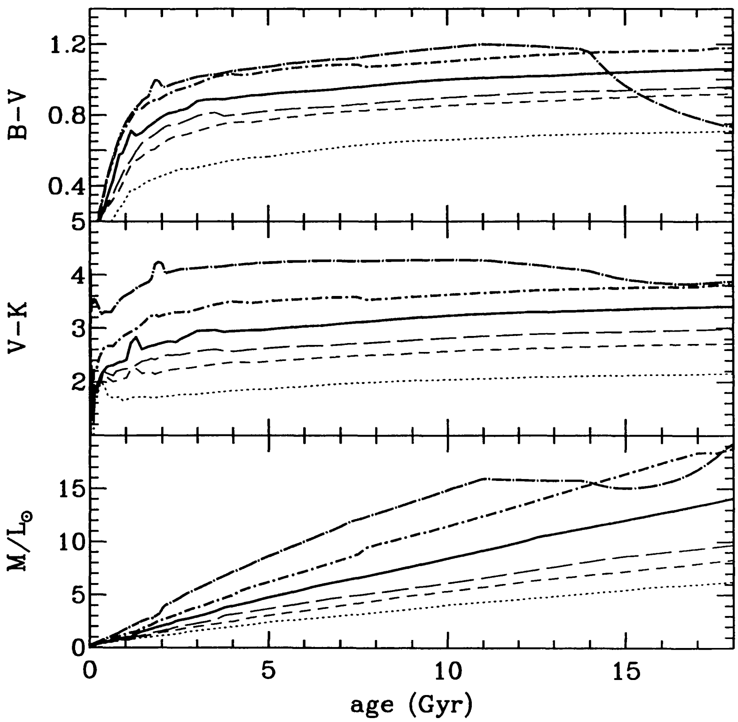

Fig. 2. Evolution in time of the $B-V$, and $V-K$ colors, and the M/L_V ratio for BC96 SSP models of different metallicities. The meaning of each line is the same as in Fig. 1.

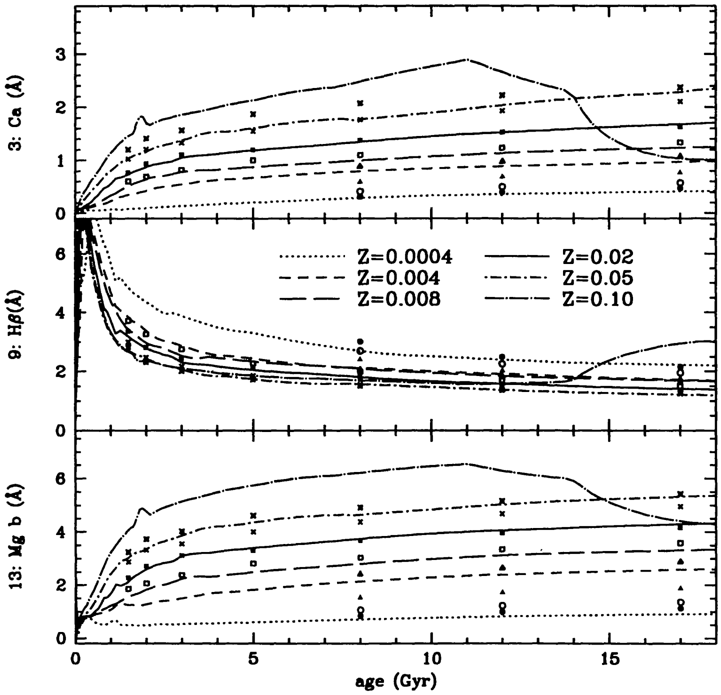

Fig. 3. Evolution in time of the Mg_b, H_β, and Ca spectral indices as defined by Worthey (1994) for the BC96 models shown in Fig. 1. The different symbols represent the values of the indices computed by Worthey for the same range in Z. Each line represents a different metallicity, as indicated in the middle panel.

highest metallicity shown, $Z = 0.10$ ($5 \times Z_\odot$). After 14 Gyr this model becomes as blue as the lower Z models. One reason for this behavior is the appearance of AGB-manqué stars at $Z = 0.10$ (Greggio & Renzini 1990). These stars skip the AGB phase and instead go through a long lived hot HB phase. However, this particular result should be taken with caution. The opacities, and hence both the evolutionary tracks and the stellar model atmospheres, are quite uncertain at this high Z. There are very few, if any, examples of galactic stars which such a high Z. On the contrary, the $V-K$ color and the M/L_V ratio show the expected tendency with metallicity, i.e., $V-K$ becomes redder and M/L_V becomes higher with increasing Z. However, even in these two quantities there is a trend at $t > 12$ Gyr for the $Z = 0.10$ model to approach the $Z = 0.05$ model.

Figure 3 shows the evolution in time of the Mg_b, H_β, and Ca spectral indices as defined by Worthey (1994) for the same BC96 SSP models shown in Figs. 1 and 2. Again, except for the $Z = 0.10$ model, the models show the expected tendency with Z and match the values computed by Worthey (1994). It should be remarked that the time behavior of the line strength indices at constant Z is due to the change in the number of stars at different positions in the HR diagram produced by stellar evolution and is not related to chemical evolution. The indices change also in chemically homogeneous populations. The H_β index is less sensitive to the stellar metallicity than the Mg_b and Ca index. Instead, the H_β index is high when there is a large fraction of MS A-type stars ($t < 1$) Gyr. The behavior of the 3 indices for $Z = 0.10$ and $t > 12$ Gyr is dominated by the presence of the hot HB (AGB-manqué) stars. Again, this prediction is uncertain and should be taken with caution.

4. MEASURING SPECTRAL EVOLUTION

It is not easy to use the age dependency of the intrinsic color of galaxies in order to measure spectral evolution because of the age-metallicity degeneracy. From Fig. 2 it can be seen that for stellar populations older than 2 Gyr, an increase in Z by a factor of 2 and a decrease in age by a factor of 3 results in almost identical optical and near IR colors (Worthey 1994). A possible cause of the lack of color evolution between distant and nearby elliptical galaxies may be that the more distant objects have a higher Z, which will compensate their tendency to be bluer because of their younger age. This is a natural consequence of the metallicity-luminosity relationship for ellipticals (Z increases with L) and the Malmquist bias (at larger distance metal

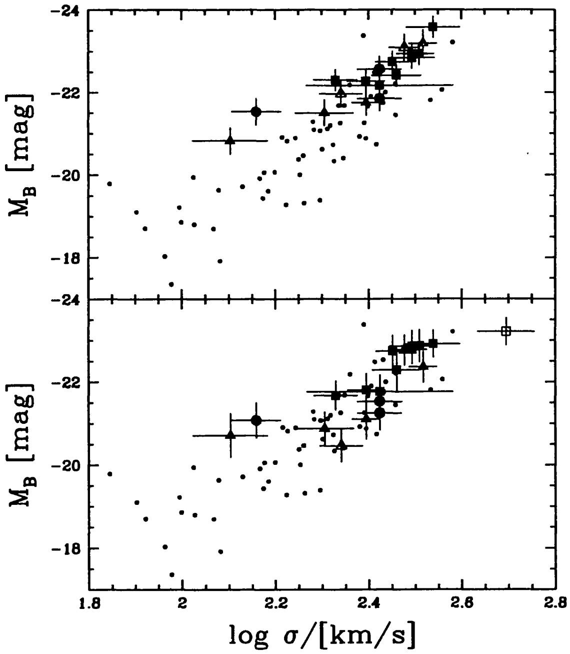

Fig. 4. The Faber-Jackson relation for Coma and Virgo ellipticals (small dots) and for ellipticals at z=0.37 ($\Omega = 1$). Top panel: rest-frame M_B; bottom panel: M_B of $z = 0.37$ ellipticals corrected for evolution, as indicated in the text. See Bender, Ziegler, & Bruzual (1996) for details.

richer, intrinsically redder, brighter galaxies are preferentially selected). This degeneracy could explain the small amount of color evolution found in brightest cluster galaxies up to $z = 1$ by Aragón-Salamanca et al. (1993) and Stanford et al. (1995), or by Hamilton (1985) in the 4000 Å break amplitude of field ellipticals. The colors of high z ellipticals cannot be used to test their evolution as long as their metallicities are not well constrained (Bender et al. 1996).

In order to study the passive evolution of elliptical galaxies, we must avoid this degeneracy in the selected galaxies. We can accomplish this goal if we select galaxies for which we know their mass, i.e., their metallicity Z. The tight correlation between the Mg_b-index and the velocity dispersion σ observed in nearby cluster ellipticals (Dressler et al. 1987) implies that, at any given σ, the combined relative spread in age and metallicity of cluster ellipticals must be smaller than 15% (Bender et al. 1993). Thus, as long as ellipticals evolve essentially passively below $z \approx 1$, we can assume that all ellipticals up to $z \approx 1$ which have similar σ, also have the same metallicity Z. Then, any reduction in the measured value of Mg_b of distant ellipticals must be due to lower age, as indicated in the lower frame of Fig. 3. The behavior of Mg_b with time is almost independent of the IMF used in the model. From Fig. 2 it follows that the decrease in Mg_b should go together with an increase in the rest frame luminosity.

The observation of the Mg_b-σ relation as a function of z gives a straightforward estimate of the evolution of the stellar populations in elliptical galaxies. Bender et al. (1996) have performed the Mg_b-σ test comparing three clusters at $z = 0.37$ with the Coma and Virgo clusters. From the small amount of evolution detected in Mg_b at a given σ, Bender et al. (1996) conclude that evolution in these galaxies takes place most likely passively. Under the assumption that galaxies with the same σ have equal Z, they conclude that the bulk of the stars in the luminous cluster ellipticals must have formed at $z > 2$, and that the most luminous objects may have formed even at $z > 4$. Since it is always possible that some young stars are present in these galaxies, these numbers represent lower limits to the epoch of cluster elliptical galaxy formation. The slope of the observed Mg_b-σ relationship at $z = 0.37$ is slightly steeper than at $z = 0$, indicating that low luminosity galaxies could be systematically younger than high luminosity galaxies. Throughout this paper I use $H_0 = 50$ km s^{-1} Mpc^{-1} and $\Omega = 1$.

From $z = 0.37$ to $z = 0$, Bender et al. (1996) find that Mg_b is reduced on average by $\Delta Mg_b \approx -0.3$Å. We can use the BC96 models to compute the expected variation in luminosity and color. From these models we find that $\Delta M_B = 1.2 \times \Delta \mathrm{Mg}_b/\text{Å}$. Then, the expected B evolution to $z = 0.37$ should be $\Delta M_B \approx -0.4$ mag. The corresponding color evolution in the rest frame is $\Delta(B - V) = -0.04$ mag and $\Delta(V - K) = -0.12$ mag. These numbers are in agreement with the measurements by Stanford et al. (1995).

Fig. 4 shows the Faber-Jackson relation for the data used by Bender et al. (1996). In the bottom panel, M_B for each of the $z = 0.37$ cluster ellipticals has been shifted by its individually calculated evolution correction $\Delta M_B = 1.2 \times \Delta \mathrm{Mg}_b/\text{Å}$. The $z = 0.37$ ellipticals fall on top of each other. Even the slope of the Faber-Jackson relation at $z = 0.37$ is similar within the errors to the locally observed slope. ¿From this figure we see that the amount of evolution derived from the Mg_b-σ relation is consistent with that implied by the Faber-Jackson relation. Changing the slope of the IMF by $\Delta x = \pm 1$ would cause a change of the luminosities at $z = 0.37$ by ca. ± 0.13 mag (BC96). Similarly, changing $\Omega = 1$ by ± 1 causes a change of the luminosities by ca. ± 0.11 mag.

5. CONCLUSIONS

- The few available observations seem to be consistent with the hypothesis that luminous cluster ellipticals evolve mostly passively in time. That is, they form stars quickly during or just after the collapse of the galaxy; the stars then age as prescribed by stellar evolution theory. Possible star formation events that may take place later on in the life of the galaxies do not seem to dominate the properties of these galaxies.
- Line strength indices may provide better indicators of evolution of the stellar population in elliptical galaxies than the photometric colors or magnitude (but see Freitas-Pacheco & Barbuy in these proceedings).
- The previous conclusions have important implications for our ideas about the epoch of galaxy formation and how well synchronized this process is required to be.
- The evolution of the stellar population in ellipticals as derived from the Mg_b-σ relation and from the Faber-Jackson relation are consistent. Within the limits of the errors in the measurements of Bender et al. (1996), there is no evidence for a very unusual slope of the IMF, nor a very unusual value of the cosmological constant Λ.
- This type of analysis should be extended to larger and deeper samples.

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