EVOLUTIONARY POPULATION SYNTHESIS

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ABSTRACT. A brief and non-exhaustive review of the main research papers on Evolutionary Population Synthesis is presented. The degree up to which these studies obey well known astrophysical constrains, such as the Fuel Consumption Theorem, is analyzed. A summary of the most significant results from the Isochrone Synthesis Spectral Evolution Models of Bruzual and Charlot (1992) concludes this presentation.

1. Introduction

Among the different techniques used in spectral synthesis, evolutionary population synthesis (EPS) has become a standard technique to study the spectrophotometric evolution of galaxies. The primary goal of EPS is to compute the time-dependent distribution of stars of various masses in the HR diagram for a given stellar initial mass function (IMF) and star formation rate (SFR). The evolving integrated spectrum of the stellar population for the assumed IMF and SFR is then derived by adding up the spectra of the individual stars, weighting each spectrum by the number of stars of each type. Without pretending to be an exhaustive review of the literature on EPS, the remaining of this section summarizes the main contributions on the subject.

The pioneer work of Tinsley (1972), followed up by Tinsley and Gunn (1976a, b) and Tinsley (1978) established the foundations of EPS and defined the general properties (IMF, SFR, age) of the EPS models that reproduced the photometric properties of various kinds of stellar systems. During the same period Searle, Sargent and Bagnuolo (1973) and Huchra (1977) developed parallel codes to study the photometric properties of star clusters and galaxies of different morphological types. Bruzual (1981, 1983) and Gunn, Stryker, and Tinsley (1981) were the first to use stellar spectrophotometric data in EPS. The prediction of detailed galaxy spectra allowed us to derive firmer conclusions on galaxy evolution than photometric studies had permitted in the past. The magnitude and color evolutionary corrections up to redshifts of cosmological interest derived from these spectrophotometric codes were more realistic than the ones derived previously from interpolated broad band fluxes. More *ad hoc* and less detailed models were constructed by Arimoto and Yoshii (1986, 1987). The evolution of these models in the UV range does not follow directly from stellar evolution, as in the previously mentioned cases, but is arbitrarily scaled according to the flux in the U band. Guiderdoni and Rocca-Volmerange (1987) introduced some refinements into EPS, such as including nebular emission and reddening by dust grains in their synthetic spectra. Their coverage of the HR diagram was more complete than in the work of previous authors.

A large amount of work on EPS has been performed by the *Italian School*. A careful set of spectral evolutionary models for elliptical galaxies has been developed by Barbaro and Olivi

B. Barbuy and A. Renzini (eds.), The Stellar Populations of Galaxies, 311–320.

(1989) in a paper that has not received due attention from other workers on the subject. The assemble of evolutionary tracks used in this paper includes all phases of stellar evolution, and an attempt is made to follow the chemical enrichment of successive generations of stars. The stellar spectra are obtained from Kurucz's (1979) set of model atmospheres. Barbaro and Olivi conclude that the UV flux in elliptical galaxies is produced by PAGB stars. A careful study of the most likely mass and chemical content of the PAGB stars producing this UV flux has been presented by Bertelli *et al.* (1989). They conclude that the final mass *vs.* metallicity relation suggested by the PAGB model of the UV emission in ellipticals is indeed compatible with stellar evolution results, provided that the correct dependence of this mass on both chemical composition and mass loss is taken into account. Buzzoni (1989) has developed an independent set of EPS models along the same lines of Barbaro and Olivi, using different evolutionary tracks and supplementing Kurucz's model atmospheres with Bell and Gustafsson (1978) models for cool stars. This code has been used by Buzzoni *et al.* to derive a metallicity scale for elliptical galaxies via a calibration of the Mg_2 index.

In parallel to the spectrophotometric models described above, there has been considerable effort invested in building purely photometric models. These models are very valuable for detailed studies of the population content of nearby stellar systems. Battinelli and Capuzzo-Dolcetta (1989) have built EPS models to study the dependence of the *UBV* fluxes and colors on time and metallicity. They discuss in detail several alternatives to explain the gap observed in the color distribution of the MC clusters, favoring a solution in terms of the high transit velocity shown by their synthetic models in the HR diagram around the $B-V$ color corresponding to the fast reddening of the clump of core helium-burning stars. Barbero *et al.* (1990) in an independent study of the emission from LMC clusters in selected far-UV bands suggest that the gap in the observed colors, at least for the LMC, is caused by the lack of clusters in the range of ages between 0.2 and 1 Gyr. Models that follow a detailed treatment of the chemical and photometric evolution in the *UBVR* bands of elliptical galaxies have been developed by Brocato *et al.* (1990). These authors conclude that the increasing UV flux with increasing metallicity observed in ellipticals is explained by the different behavior of stars of different metal content during the post-HB phases. Mazzei *et al.* (1991) built a detailed photometric model in the *UBVRIJKLMN* bands for the evolution of disc galaxies based on the evolutionary tracks of Bertelli *et al.* (1990). This model, which incorporates diffuse dust emission, is applied successfully to our own galaxy.

Charlot and Bruzual (1991, hereafter CB91) assembled a library of stellar evolutionary tracks for solar metallicity, largely based on Maeder and Meynet (1989), suited for an isochrone synthesis approach. At any age an isochrone is derived by interpolation of the evolutionary tracks in the HR diagram. By construction, all evolutionary stages are included in the isochrone. This insures a smooth time dependence of all the properties of the synthetic population. The photometric models of CB91 were shown to reproduce well the observations of nearby stellar populations in the *UBVRIJKL* bands. Bruzual and Charlot (1992, hereafter BC92) have extended the models of CB91 by adding a spectrophotometric stellar library which covers the range from the far UV to the far IR and is essentially based on observational data for solar metallicity stars. The evolutionary tracks used by BC92 contain some improvements over those of CB91. The main sequence lifetime of the stars with masses between 1.3 $M_\odot$ and 2.5 $M_\odot$ have been revised as indicated by Maeder and Meynet (1991) and Bertelli *et al.* (1991). The revised lifetimes range from about 90% (2.5 $M_\odot$) to about 50% (1.3 $M_\odot$) of the original values. Following the prescriptions of Magris and Bruzual (1992, hereafter MB92) the treatment of the post-AGB evolution of low and intermediate-mass stars was refined. The final tracks include the evolution of all stars initially less massive than 7 $M_\odot$ as planetary nebulae, bare PN nuclei, and through the white-dwarf cooling sequence. In section **3** I will discuss some of the results of CB91, BC92, and MB92. A detailed comparison of these results with previous work is beyond the scope of this short presentation (see BC92 for details).

2. The Fuel Consumption Theorem and Evolutionary Population Synthesis

Early EPS models were severely criticized by Renzini (1981) and Renzini and Buzzoni (1983, 1986, hereafter RB86) on the grounds that these models *more or less dramatically violate the prescriptions of the Fuel Consumption Theorem,* (FCT) *and should therefore be viewed with extreme caution even when they apparently provide satisfactory fits to the observations.* The FCT states that "the contribution of stars in any given post-main sequence stage to the integrated bolometric luminosity of a simple stellar population (SSP) is directly proportional to the amount of fuel burned during that stage". Figure 5 of RB86 (hereafter RB86-F5) shows the fractional contribution of the various evolutionary stages to the integrated bolometric luminosity of a SSP as a function of the age of the population, derived by these authors from the FCT for specific assumptions about stellar evolution.

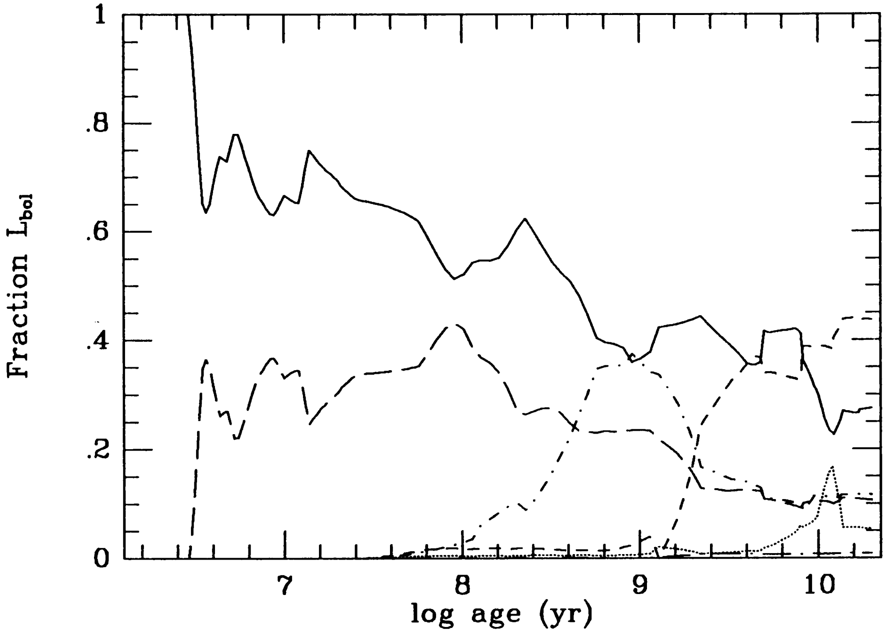

Figure 1. Fractional contribution of the various evolutionary stages to the integrated bolometric luminosity of a SSP as a function of time according to BC92. The different curves correspond to the following stages: MS (*solid line*), SGB (*dotted line*), RGB (*dashed line*), CHeB (*long-dashed line*), AGB (*dot and short-dashed line*), and PAGB (*dot and long-dashed line*). The Salpeter (1955) IMF was assumed.

Renzini's criticism is certainly valid for the early work on EPS by Tinsley (1972, 1978), Tinsley and Gunn (1976a, b), Bruzual (1981, 1983), Gunn, Stryker, and Tinsley (1981), Arimoto and Yoshii (1986, 1987), and Guiderdoni and Rocca-Volmerange (1987). Most of the papers attributed above to the *Italian School* do make an attempt to obey the prescriptions of the FCT and, in particular, to follow literally RB86-F5 (see also Wyse 1985). Unfortunately, the exact shape of the lines shown in RB86-F5 depends on the set of evolutionary tracks used in the computation. CB91 and BC92 have shown that their isochrone synthesis algorithm do strictly obey the FCT. However, the evolutionary tracks used by BC92 are independent from those used by RB86, and the fractional contributions to the total light derived by BC92 shown in Figure 1 do differ from those of RB86-F5.

The fluctuations seen in some of the curves in Figure 1 are intrinsic to the stellar tracks, since the contribution of a given evolutionary phase does not always vary smoothly with decreasing ZAMS mass. A striking feature is that MS stars dominate the integrated light of the burst population from early ages on until about 8 Gyr, contrary to the behavior shown in RB86-F5. This predominance of MS stars is essentially due to the inclusion of convective overshooting in the Maeder and Meynet (1989) stellar tracks. Convective overshooting lengthens the MS lifetime of stars more massive than 1.1 $M_\odot$. Since lower-mass stars do not develop a convective core on the MS, RGB stars dominate the bolometric light at later ages.

Figure 2 shows the fractional contribution of AGB stars to the integrated bolometric luminosity of a SSP according to BC92. The agreement of the model and the data is quite good, especially since the youngest clusters may be contaminated by M supergiants mistaken for AGB stars (Frogel *et al.* 1990). The contribution of the AGB stars becomes significant at much earlier ages in RB86 than in CB91 and BC92. The reason for this discrepancy is the assumed upper-mass limit for stars to go through the AGB phase. In the Maeder and Meynet (1989) tracks used by CB91 and BC92, stars with $m \leq 7 M_\odot$ go through the double-shell burning phase that characterizes the AGB, whereas this limit is higher for the tracks of RB86.

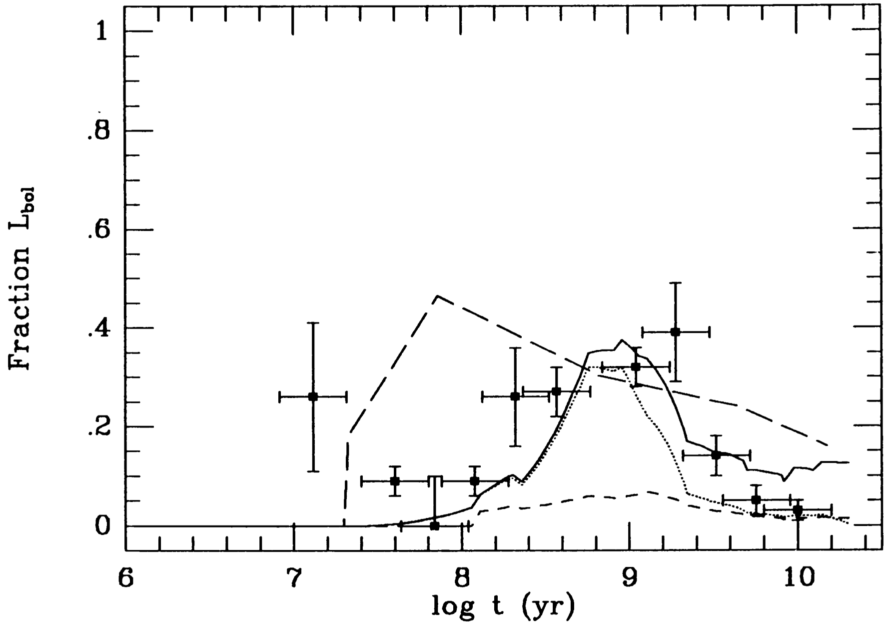

Figure 2. Fraction of the integrated bolometric light of a SSP with the Salpeter (1955) IMF accounted for: AGB stars brighter than M_{bol} = -3.6 (*dotted line*), all AGB stars (*solid line*), and TP-AGB stars (*short-dashed line*), according to BC92. The data points are the contribution observed in the MC clusters by Frogel *et al.* (1990). The long-dashed line is the contribution predicted by RB86-F5.

3. Isochrone Synthesis Spectral Evolution Models

BC92 have used their isochrone synthesis models to derive a best-fitting spectrum for several well-observed nearby galaxies. The selection of this best fit is done objectively, once a model

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with a given IMF and SFR is specified, and refers only to the age at which the model resembles most closely the observed spectrum. No attempt was made by BC92 to derive the optimal IMF or SFR for a given galaxy.

Figure 3 shows a comparison of the predicted spectral energy distribution of a 1 Gyr burst model, in which star formation takes place during the first Gyr of the life of the galaxy, with that of an *average* elliptical galaxy, at the best-fitting age of 13 Gyr. For details about this average spectrum see BC92. The fit is excellent over the whole spectral range, and no systematic trend is observed in the behavior of the residuals with wavelength. The main stellar absorption features in the observed spectrum and the amplitude of the 4000 Å break are well reproduced by the model. The quality of the fit in the UV, optical, and the near-IR, constitutes a major improvement over earlier population synthesis models (Bruzual 1983, Guiderdoni and Rocca-Volmerange 1987).

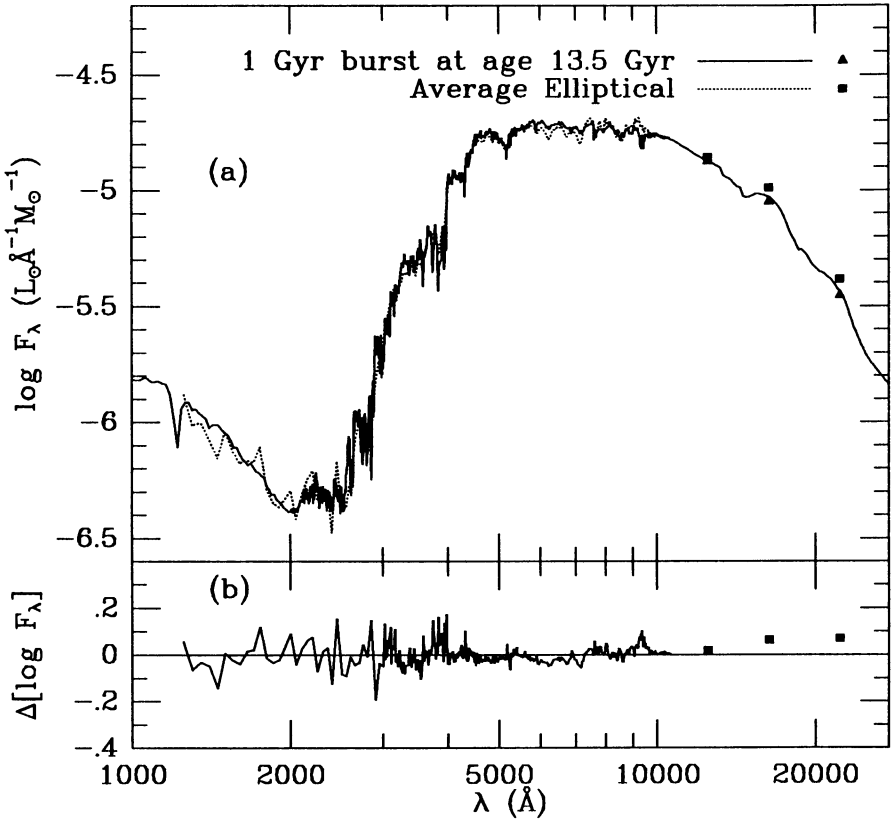

Figure 3. *(a)* Comparison of the 1 Gyr burst model of BC92 at age 13 Gyr (*thin line and triangles*) with the *average* observed spectrum of quiescent elliptical galaxies (*thick line and squares*). The squares and the triangles correspond to the fluxes at the effective wavelengths of the J, H, and K bands. The Salpeter (1955) IMF was assumed. *(b)* Residual of the comparison in panel *(a)*.

The UV-rising branch of quiescent elliptical galaxies (Burstein *et al.* 1988) is thus explained by BC92 as a natural consequence of late stellar evolution, superseding the conclusions of models without post-AGB stars that required recent star formation (Bruzual 1983, Guiderdoni and Rocca-Volmerange 1987), but in agreement with Barbaro and Olivi (1989).

Figure 4 compares a model with constant SFR with the observed spectral energy distribution of the irregular galaxy NGC 4449, assembled from *IUE*, optical, and near-IR data by Ellis and Bruzual (1983, unpublished). The best-fitting age in this case is 1 Gyr. The model does not include nebular emission by gas and hence it cannot reproduce the observed emission lines. The residuals between model and data are very small, except blueward of 1500 Å, where the model shows an excess of UV radiation. Reducing the proportion of massive stars in the IMF decreases this excess, but the 4000 Å break then rises in the model, and makes the fit worse in the optical. Alternatively, extinction by internal dust in this galaxy may reduce the ultraviolet flux.

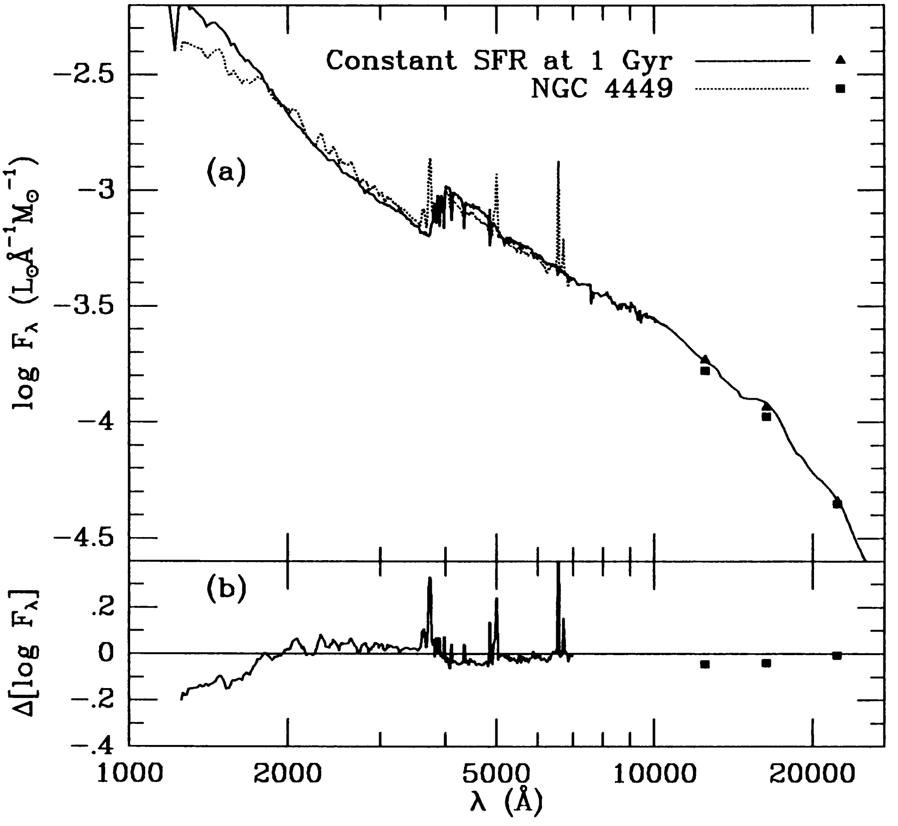

Figure 4. *(a)* Comparison of the constant SFR model of BC92 at age 1 Gyr (*dotted line and triangles*) with the observed spectrum of the irregular galaxy NGC 4449 (*thick line and squares*). The squares and the triangles correspond to the fluxes at the effective wavelengths of the J, H, and K bands. The Salpeter IMF was assumed. *(b)* Residuals of the comparison in panel *(a)*.

The spectra of galaxies of other morphological types are explained by BC92 with exponentially decreasing SFR models with characteristic time τ. The model fits are similar to the ones shown in Figures 3 and 4, except that the age inferred for the Coleman *et al.* (1980) Sdm (constant SFR, age = 2.5 Gyr) is older than the one found for NGC 4449 due to the redder spectrum of the former. Models with intermediate time scales of star formation and the Salpeter IMF can reproduce reasonably well the spectra of Sbc (τ = 4, age = 15 Gyr) and Scd (τ = 7, age = 14.5 Gyr) galaxies in the Coleman *et al.* (1980) sample.

The significance of the best-fitting ages is weak in the case of the average elliptical, whose spectrum can be fitted almost equally well by the 1 Gyr burst model at ages in the range 11 to 16 Gyr. The age for NGC 4449 is more strongly constrained by the rapid increase of the 4000 Å break as old stars accumulate. The ages and τ derived for the Sbc and Scd galaxies are not rigidly constrained by the observed spectra. Similar fits are obtained with shorter or longer τ's at younger or older model ages, respectively.

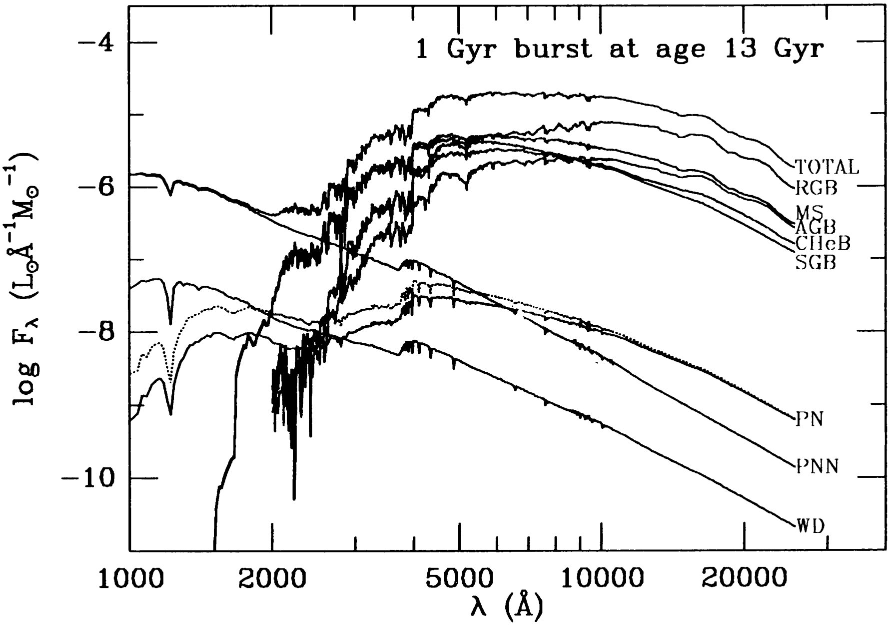

Figure 5. Contribution of stars in different groups to the total spectral energy distribution of a 1 Gyr burst model at 13 Gyr for the Salpeter IMF (PNN = bare PN nucleus). The dotted line next to the PN contribution corresponds to the case where extinction of the core radiation by the surrounding nebula is ignored. The vertical scale refers to a total mass in stars of 1 $M_\odot$.

Figure 5 shows the contribution to the total spectral energy distribution of the 1 Gyr burst model, at 13 Gyr, of different stellar groups. The spectrum blueward of 2000 Å is entirely dominated by low-mass PAGB stars whose envelopes have dissipated. MS and SGB stars account for most of the light between 3000 Å and 4000 Å, and the RGB produce more than half of the light at longer wavelengths. The exact shape of the spectrum from the optical to the near-IR, however, is a subtle combination of various nearly equivalent contributions. Note that PN have a negligible contribution to the integrated spectrum, even if one ignores the absorption by the envelope of the core radiation (*dotted line*).

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MB92 have analyzed the UV upturn seen in elliptical galaxies using the evolutionary models of BC92. Figure 6 shows the average spectral energy distributions for 3 representative groups of galaxies with different levels of UV flux from the Burstein *et al.* (1988) sample. Galaxies with UV flux level like N4649 (top frame in Figure 6) are modeled by MB92 with a 14 Gyr old stellar population (consistent with Bertelli *et al.* 1989) in which the SFR corresponds to an initial burst of 100 $M_\odot\ yr^{-1}$ lasting for 1 Gyr plus a *residual* continuing star formation of 0.03 $M_\odot\ yr^{-1}$. Normal PAGB stars, included in the BC92 stellar library, contribute mainly at $\lambda \leq 2200$ Å, and cannot reproduce the flux level observed in these systems in the range 2200-2600 Å. Other possible source of this excess UV flux besides MS stars have been explored by Greggio and Renzini (1990). On the contrary, the spectra of galaxies with an intermediate value of (1550–V) (like N4472, middle frame) are well fitted by a 1 Gyr burst BC92 model seen at 13 Gyr (Figure 3). In this case the UV flux is produced by normal PAGB stars, resulting from the evolution of a quiescent stellar population.

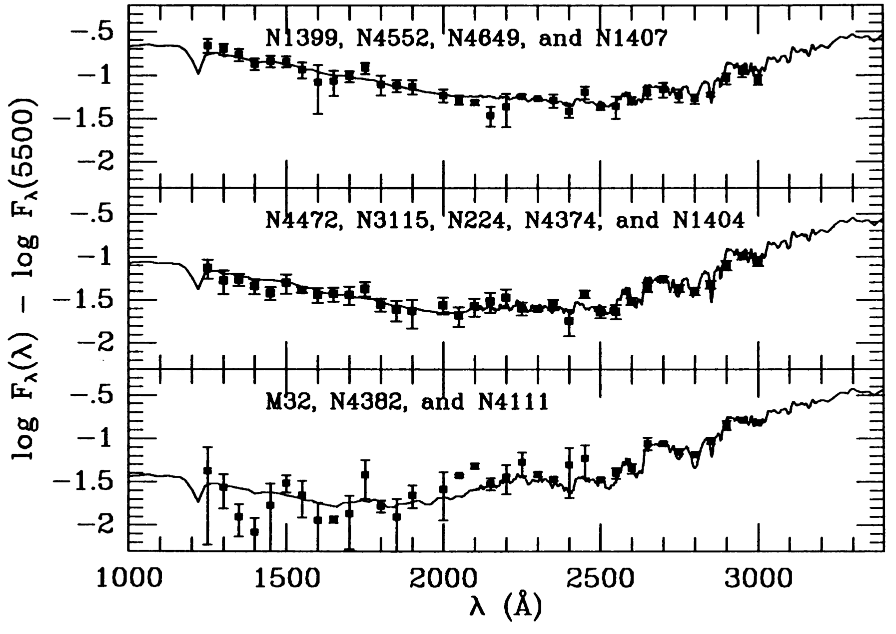

Figure 6. The data points represent the average spectral energy distributions for 3 representative groups of elliptical galaxies defined by Burstein *et al.* (1988). The error bars represent the dispersion around the mean flux. The lines correspond to the models by MB92 described in the text. The Salpeter IMF was used in the models.

The spectra of galaxies like M32 (bottom frame) can be understood if the stellar system underwent two events of star formation: an initial 1 Gyr burst, and a second burst of the same duration at an approximate age of 6 Gyr. Each of these bursts encompasses half of the galaxy mass seen through the *IUE* aperture. This result is in accord with O'Connell (1986), and Bertelli *et al.* (1989), but was questioned by Greggio and Renzini (1990).

Conclusions

Considerable progress has been achieved in recent years in the field of EPS. Complete libraries of evolutionary tracks and spectra that had been incorporated, together with increasingly sophisticated synthesis algorithms, have allowed several authors to develop EPS codes that overcome most of the problems present in early models. In particular, the isochrone synthesis models of BC92 can reproduce reasonably well the observed spectral or photometric properties from the UV to the near-IR of nearby galaxies of various Hubble types, in which young massive stars, old low-mass stars, or mixtures of stars of all masses and ages produce the light. These models constitute therefore a reliable mean to investigate the spectral evolution of any stellar population. The possibility that some of the other evolved hot star candidates (Greggio and Renzini 1990) contribute significantly to the UV flux is not excluded, but for many ellipticals, the normal evolution of stars beyond the AGB produces enough flux to account for their UV rising branch. Spectrophotometric models which also follow the chemical evolution of the stellar population (e.g. Barbaro and Olivi 1989, Brocato *et al.* 1990) still need further development.

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Discussion

Rocca-Volmerange: There is a real danger to use, as you did, two different types of evolutionary tracks in population synthesis models. Discontinuities in evolutionary time, bolometric magnitude, and effective temperature are observed between the 1 $M_\odot$ evolutionary track from Maeder and Meynet (1989) and the 0.9 $M_\odot$ track from Chiosi's group.

Bruzual: This is certainly true and I have pointed that out myself in several occasions (Bruzual 1981, 1983). Charlot and myself were extremely careful to insure that these discontinuities did not affect the final results of our isochrone synthesis models. The revision of the MS lifetime of the stars with masses between 1.3 $M_\odot$ and 2.5 $M_\odot$ indicated by Maeder and Meynet (1991) and Bertelli *et al.* (1991) tends to iron out the discontinuities that you mentioned.

Rocca-Volmerange: The observed dispersion in $V-K$ of the MC clusters is likely explained by the stellar evolution of cold stars. Why does your sequence $V-K$ *vs.* age appear so smooth?

Bruzual: The models that I have discussed include the smooth evolution of the stellar population, and hence the predicted color *vs.* age lines show a smooth behavior. No attempt has been made to incorporate into the isochrone synthesis models the stochastic effects produced by fluctuations in the number of giant stars sampled by the aperture of the telescope, or fluctuations due to the relatively small numbers of stars present in clusters, etc. An approach to the inclusion of these effects in EPS models is discussed by Bertelli *et al.* (1991).

Vanbeveren: A stellar population may contain a significant fraction of interacting binaries. Since you do not include the evolution of close binaries in your models, how reliable then is a comparison between observations and theoretical models?

Bruzual: As far as I know no EPS model includes the evolution of close binary systems. I still think that the comparison of the model spectra and the observations has some significance in as much as it refers to the accuracy with which the observed spectral features are reproduced by the models. As long as the effect of close binary evolution is to populate parts of the HR diagram that would otherwise be void of stars, then it is dangerous to derive conclusions from current EPS models about the SFR, IMF, or age of the dominant population in a stellar system.

Ostriker: As you noted binaries are omitted. In globular clusters the interacting (WD + MS) systems contribute, I believe, a significant amount at UV wavelengths. Did you compare your UV spectra with those observed from globular clusters to see if close interacting binaries make a significant contribution?

Bruzual: No, I have not performed this comparison. I think that this is a very good suggestion and I will try to do this comparison in the near future.

Torres-Peimbert: How sensitive are your color predictions for evolved galaxies to the duration of the star formation burst?

Bruzual: Very insensitive. A few Gyrs after star formation ends, the colors for different models are independent of the assumed duration of the star formation burst.

Serrano: I believe that your solutions are not unique. It will be interesting to display iso-χ^2 contours in parameter space. I expect the solutions not to be very sensitive to changes of parameters along the metallicity axis.

Bruzual: This is correct and we are working in that direction. I have done some work in collaboration with D. C. Koo on the prediction of the number counts and color distributions of faint galaxies in which we do compute iso-χ^2 contours. This will be extended to spectral synthesis in the future.