Highlights of Spanish Astrophysics VI, Proceedings of the IX Scientific Meeting of the Spanish Astronomical Society held on September 13 - 17, 2010, in Madrid, Spain. M. R. Zapatero Osorio et al. (eds.)

Tracing the evolution of galaxies with stellar population models

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Abstract

The stars that make a galaxy are born in different environments and times. Thus, their stellar populations contain rich information about the different stages through which the galaxy evolved. In the last couple of decades stellar population synthesis models have been crucial to interpret the observations of galaxies and to infer their star formation and mass assembly histories. The goal of this review is to discuss the main uncertainties in the evolutionary synthesis models and their impact on the analysis of the galaxy spectra. A summary of the most recent achievements obtained in stellar populations studies and the future challenges in the context of the Spanish astronomy are presented.

1 Overview

Luminous matter represents only a small fraction of the energy of the universe but is a very crucial component to understand the formation and growth of galaxies. Luminous matter holds, in fact, the imprints of the star formation and mass growth history of the universe because the resulting spectrum of light emitted by a galaxy depends on how stars form and evolve over time. Thus, a galaxy spectrum can be seen as a fossil record of its history, containing information from all its stellar generations.

Much progress has been obtained in this decade through the extensive photometric and spectroscopic surveys at intermediate and high redshifts, that have allowed us to know how galaxy matter grow and how the star-formation history is over cosmic time (e.g. [50]). Complementary to these promising high-redshift works, surveys on the local universe, like the Sloan Digital Sky Survey (SDSS), have also provided us with thousands of high quality spectra that give information about the star formation rates in galaxies, and the gas-phase and stellar metallicities over cosmic time (e.g. [12, 13, 30]). These surveys have also pointed out the bimodal distribution of the galaxy populations in colors, masses, ages, metallicities and morphology (e.g. [31, 32, 62, 44]). These results indicate that massive galaxies as seen nowadays have stellar populations formed at early times (result known as “downsizing”).

All these works show the relevance of stellar population studies to constrain the galaxy formation models. Because different formation scenarios can leave distinct imprints in the stellar content of galaxies, we are convinced that deriving the stellar population properties in different examples of galaxies we can know when and how the galaxies formed and how they evolve (for example from the blue cloud to the red sequence).

Since the pioneer articles by Tinsley [58, 59] many works have reported results about the formation and evolution of galaxies based on stellar population synthesis models. The aim of this paper is to discuss the recent advances and main uncertainties associated to evolutionary synthesis models and how they affect to the determinations of the stellar populations properties. The Spanish community is very active in this field and considering that this plenary talk is given in the Scientific Meeting of the Spanish Astronomical Society, I would like first to present a brief summary of the Spanish contribution to this issue.

2 Stellar populations models: the Spanish contribution

Evolutionary synthesis models is a very successful and simple tool to predict the observational properties of any ensemble of stars and derive the stellar masses, ages, and metallicities (and abundance ratios) of the stellar population of galaxies. The main ingredients are the initial mass function (IMF), the stellar evolutionary tracks, and the stellar libraries. The last decade was very fruitful with several codes (e.g. Pegase [19]; Starbursts99 [39]; Galaxev: [2]; [40]; Galev: [34]) which initially were optimized to some particular phases of the stellar evolution. The Spanish community has been very active in this field by developing codes and building stellar libraries. I briefly comment some of these works and in which aspects were optimized.

Codes:

- Wolf-Rayet stars and Far-IR emission in starbursts [43].
- Emission lines from HII regions [20].
- Effect of binaries in the models [7]; X-ray emission.
- Early type galaxies [64, 63]; CaII triplet [65]; high spectral resolution models [66].
- High-spectral resolution models [25, 26].
- Models with the most up to date stellar atmosphere spectra [45].

Stellar Libraries:

- Synthetic stellar spectra with Balmer and He lines [17, 23].
- UV lines at $\lambda \leq 1200$ Å [24].
- CaII triplet [18, 3].

- High-spectral resolution stellar libraries at optical wavelengths (Granada library: [42]; MILES: [54]).
- NIR and CO band [41].

Another relevant aspect in which the Spanish astronomers are contributing significantly is to the developing of models that take into account the stochastic effects of the stellar populations. The stellar population models always assume the existence of a probabilistic distribution function that describe the mean value of the relative contribution of different populations to the integrated light. In this way, the luminosity (and any other property) of a stellar population with N stars can be scaled to the luminosity $L_{\rm nor}$ of a stellar population with $N_{\rm nor}$ stars. But if the number of stars N is low, the most probable number in a given evolutionary state will differ significantly from the expected mean value. To account for these problems, Cerviño and collaborators (e.g. [6, 8, 5]) have developed a probabilistic formulation of the models. They have also proposed a simple rule called "low luminosity limit" that states that the luminosity of any stellar population has to be at least 10 times higher than the luminosity of the most luminous star in the model to be well represented by the mean values of the properties.

3 Ingredients and uncertainties in the models

3.1 Initial mass function

The IMF has a direct impact on all the models calculations. In most codes, the IMF is assumed to be a power-law of Salpeter index above a few solar masses [53] and a log-normal [9] or shallower power-law [35] for masses below solar. Although there is no clear evidence that the IMF varies strongly and systematically with the initial conditions and/or environment after the first generations of stars (see the recent review by [1]), this is the first ingredient in the models that astronomers like to change to reproduce the observational parameters of a stellar population. The uncertainties on the upper and lower mass limits and the slope have a significant impact on the predicted mass, luminosity, and star formation rate that have important consequences when the results of the assembly and star formation history over the cosmic time are compared. The IMF is very uncertain at masses $0.8 \leq m \leq 2$ $M_{\odot}$, and this mass range is very critical for galaxies at ages older than 1 Gyr because the main-sequence turnoff of these populations is ~ 1 $M_{\odot}$. The IMF uncertainty induces a shift in the mass-to-light ratio in some bands up to a factor 2, and can even change the color evolution of a galaxy by 0.1 mag in V–K at intermediate ages [16].

3.2 Critical evolutionary phases

(a) Early phases: Uncertainties associated with the evolution of massive stars have a relevant impact on galaxies with on-going star formation, in particular at wavelengths like the rest-frame ultraviolet that is dominated by O and B stars. Uncertainties in the stellar models (e.g. the rotation, see the models by [67], magnetic fields, and the mass loss-rates) and also the lack of realistic stellar libraries impact on the determination of properties such as the Lyman continuum photons (see e.g. [45]), ages and metallicity. Furthermore, binarity has also a strong impact on the evolution of Wolf-Rayet stars [7].

(b) Thermally pulsating asymptotic giant branch: TP–AGB phase is a very short-lived phase in the AGB that happens when the main energy source comes from a double burning shell: an outer shell of H plus an inner He shell that switches every 10^4 to 10^5 years producing thermal pulsing. When the dredge up happens, the star changes its composition converting into a carbon star after several dredge ups. This phase is very relevant for stellar populations of 0.1 to 1 Gyr. It is difficult to include in the models because the thermal pulses are variable in effective temperature and luminosity, and thus, the position in the HR diagram changes. In addition, the stellar spectra are rare [37]. This phase is relevant because dominates the NIR bands, and produces a significant uncertainty in the K band luminosity. In addition, different treatment in the models (isochrones [2] versus fuel consumption theorem [40]) give different results that produce a factor 2 difference in mass. However, new computations by Charlot & Bruzual predict 60% more flux at K band than their previous models [2], being in better agreement with [40] models. Conroy et al. [16], who have computed models including uncertainties in the luminosity and effective temperatures of the TP–AGB stars, claim that reasonable changes in these two parameters can change $V{-}K$ up to 0.5 mag. This uncertainty is significant for example to derive the mass of galaxies at redshift 2–3, in which the dominant stellar population is ~ 1 Gyr old.

(c) Horizontal branch: HB contains low-mass stars ($m \leq 1$ $M_\odot$) that have evolved from the RGB and are in the core He burning phase. The morphology of the HB is complex because it is very sensitive to the mass-loss in the RGB phase, and because HB stars can be luminous red or blue hot stars. This phase, in particular the blue HB stars (BHB), is relevant to explain the UV up turn in the spectra of elliptical galaxies that can be confused with recent star formation. Furthermore, the BHB can contribute significantly to the Balmer lines of the integrated light of an old stellar population affecting significantly to the age determination (e.g. [11]). Models that actually include the BHB in their computations are [40, 49, 29]. Conroy et al. [16] have computed models allowing the fraction of blue HB to be variable. This parameter is turned on at ages ≥ 5 Gyr producing a significant impact on the UV and blue colors, but does not significantly alter the evolution of colors at later times, but rather it amounts to an approximately constant blueward offset.

3.3 Stellar libraries

The stellar libraries are also an important ingredient in evolutionary synthesis models. The libraries must be formed by a set of stellar spectra covering a homogeneous range of effective temperature, gravity and metallicity. In terms of spectral range, spectral resolution and homogeneity in the parameter ranges the stellar libraries have improved significantly in this decade. Figures 1 and 2 show a summary of the main characteristics of the most up to date

Library	FWHM (Å)	Spectral Range (Å)	No. Stars		
ELODIE	0.1	4100-6800	1388	Echelle	Prugniel & Soubiran 2004 PEGASE (Le Borgne et al 2005)
STEBLIB	3.0	3200-9500	249	Flux calibrated	Le Borgne et al 2003 GALAXEV (BC03)
INDO-US	1.0	3460-9464	1273	Poor flux calibrated	Valdés et al 2004 GALAXEV (CB07)
MILES	2.3	3500-7500	985	Flux calibrated	Sánchez-Blázquez et al 2006 GALAXEV (CB07) Vazdekis et al.
HNGSL		1700-10200	Few 100	Flux calibrated	Heap & Lanz (2003) GALAXEV (CB07)

Figure 1: The table shows the most relevant empirical stellar libraries at optical wavelength published in this decade.

empirical and synthetic stellar libraries at optical wavelengths. Let me highlight here the characteristics of the MILES [54] and Granada [42, 26]stellar libraries.

MILES: this library contains 985 stars spanning a large range of stellar parameters. The spectra were obtained at the INT in the Roque de Los Muchachos Observatory in La Palma, and they cover from 3500 to 7500 Å with a spectral resolution of 2.3 Å FWHM. The spectra are very well flux calibrated. This library represents a significant improvement not only with respect to the Lick/IDS library, but also with respect to STELIB, INDO-US and ELODIE (see Figure 2 in [54]). However, the library has still only a small number of hot stars (over 15000 K).

Granada: this library contains 1654 high-resolution stellar spectra with a sampling of 0.3 Å covering the wavelength range from 3000 to 7000 Å. The library was computed using the latest improvements in stellar atmospheres, non-LTE line-blanketed models for hot stars ($T_{\rm eff} \geq 27500$ K) [28, 38], ATLAS9 [36] for stars with $T_{\rm eff}$ between 4500 K and 25000 K, and PHOENIX line blanketed models [27] for cool stars (3000 K $\leq T_{\rm eff} \leq$ 4500 K). The gravity ranges from $\log g = -0.5$ to 5.5, and the models are computed for five metallicities from twice solar to 1/20 solar ($Z = 0.04, 0.02, 0.005, 0.001$ and 0.002). The full set of synthetic spectra are available in our website http://www.iaa.es/∼rosa.

To study the impact of stellar libraries on the determination of the age and metallicity in the models we [22, 11] have fitted the integrated optical spectra of a sample of stellar clusters mainly in the Magellanic Clouds with a suite of modern evolutionary synthesis models for single stellar population. The combinations of model plus spectral library employed in this investigation are Galaxev/STELIB, Vazdekis/MILES, SED@/Granada, and Galaxev/MILES+Granada, which provide a representative sample of models currently available for spectral fitting work. The comparison between the properties derived from these spectral fits and from the literature data (obtained from color-magnitud diagram and the S-CMD method) on these nearby, well studied clusters allow us to estimate the uncertainties in the models due to stellar libraries. Figure 3 shows an example of the different fits for the stellar cluster NGC 2010. We find that: (1) All models are able to derive ages in good

Models	Resolution	Spectral Range(Å)	Atmosph	Teff Log g	Metallicity
Rodríguez-Merino et al 2005	50000	850-4700	Kurucz	3000-50000 Log g= 0--5	[M/H]= -2.0, -1.5, -0.5, 0.0, 0.3, 0.5
Munari et al 2005	20000 2000	2500-10500	Kurucz	3500-47500 K log g= 0--5	-2.5<[M/H]<0.5 [α/Fe]=0.0, 0.4
Coelho et al 2005	High	3000-18000	Kurucz	3500- 7000 K log g= 0--5	[M/H]= -2.5, -2.0, -1.5, -1.0,-0.5, 0.0, 0.2, 0.5 [α/Fe]=0.0, 0.4
González Delgado et al. 2005 Martins et al 2005	0.3 Å Granada library	3000-7000	TLUSTY + Kurucz +PHOENIX	3000-55000 K log g= -0.5--5	Z= 0.04, 0.02, 0.008, 0.004, 0.001

Figure 2: The table shows the most relevant synthetic stellar libraries at optical wavelengths published in this decade.

agreement both with each other and with literature data, although ages derived from spectral fits are on average slightly older than those based on the S-CMD method as calibrated by [21]. (2) There is less agreement between the models for the metallicity and extinction. In particular, Galaxev/STELIB models underestimate the metallicity by $\sim$0.6 dex, and the extinction is overestimated by 0.1 mag. (3) New generation of models using the Granada and MILES libraries are superior to STELIB-based models both in terms of spectral fit quality and regarding the accuracy with which age and metallicity are retrieved. Accuracies of about 0.1 dex in age and 0.3 dex in metallicity can be achieved as long as the models are not extrapolated beyond their expected range of validity.

3.3.1 Non-solar abundance ratios

Another relevant source of uncertainties in the models is the inconsistency between the chemical abundance pattern of the stellar libraries in the models and the data. Usually the synthesis stellar libraries are computed with solar-scaled abundance ratios, and empirical stellar libraries are built with stars in the solar neighborhood, so at low-metallicity the stars are α-enhanced ([α/Fe] $\sim$ 0.3). Massive elliptical galaxies are not well modeled with solar abundance ratios, and the mismatch between their "α-enhanced" stellar populations [69] and evolutionary synthesis models which do not take this into account lead to clearly identifiable residuals in spectral fits (e.g. [48]). This mismatch gives results that are inconsistent and depend on the Lick indices used, for example: a) younger ages and over-solar metallicity with Hβ–Mg index or b) older ages and sub-solar metallicity stellar population with the Hβ–Fe index.

The initial steps to produce models with non-scaled abundance ratios were done to calculate the response of the Lick indices to changes in abundance ratios (e.g. [61, 56, 57, 55]). More progress is done by producing isochrones with variable [α/Fe] (e.g. the Teramo group [51]), and stellar libraries (e.g. [14, 46]) and evolutionary synthesis models [49, 15]. Furthermore, progress is obtained by producing differential stellar population models that

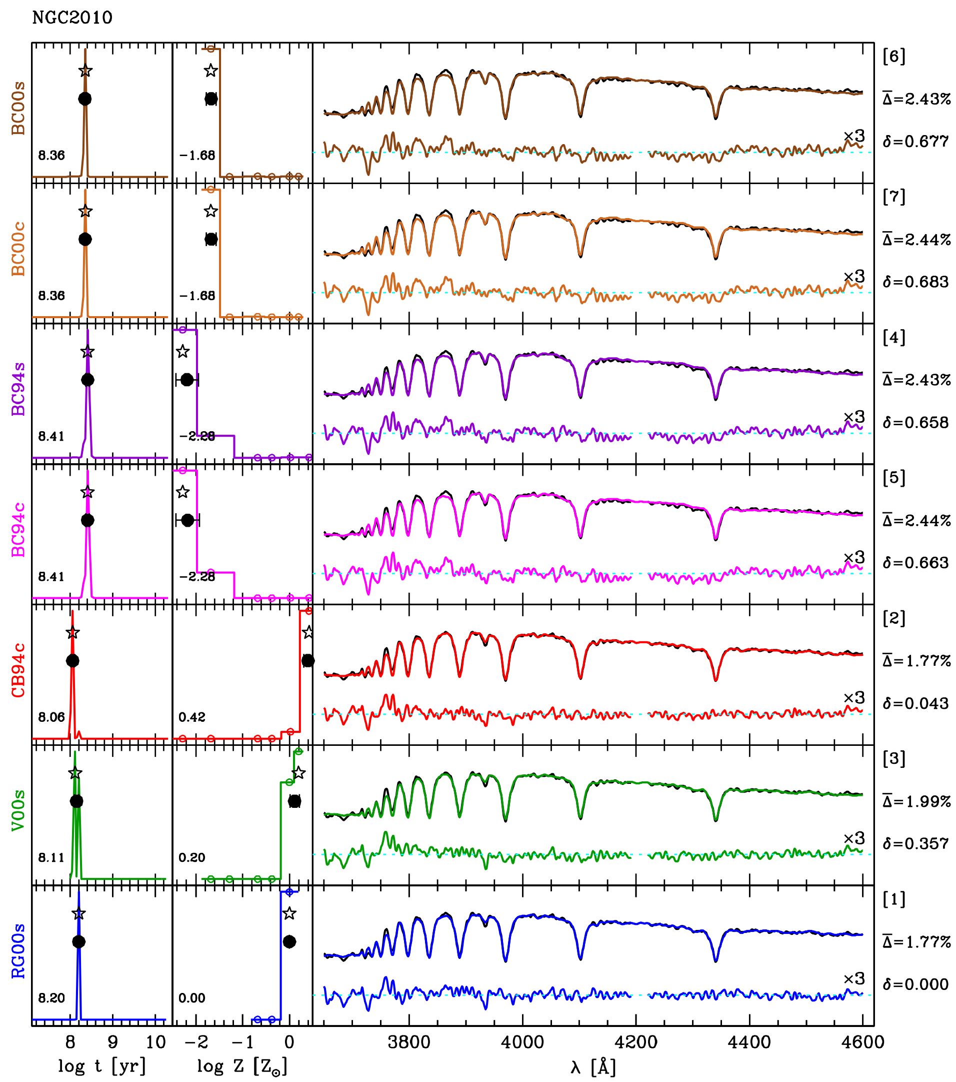

Figure 3: Comparison of spectral fits to NGC 2010 obtained with 7 different evolutionary synthesis models, labeled in the left axis: BC are the Bruzual & Charlot (2003)[2] models with the Padova 2000 (BC00c, BC00s) or Padova 1994 (BC94c, BC94s) evolutionary tracks; CB are the Charlot & Bruzual models (2010)[10]; V00s the Vazdekis et al.[66] models; and RG00s the González Delgado et al.[26] models. The symbols "s" and "c" are for Salpeter and Chabrier IMF, respectively. Values of the mean percentage residual ($\overline{\Delta}$) are listed to the right of each panel, where the number in brackets indicate the χ^2 fit quality ranking, and $\delta = (\chi^2 - \chi^2_{\rm best})/\chi^2_{\rm best}$. The left panels show the probability distribution functions of *age* and *metallicity*. A solid circle with error bars marks the mean ±1 sigma estimates. The numbers correspond to the best fit *age* (left most panel) and *metallicity* (middle), whose values are also marked by a star. In the middle panel, open circles are plotted in each of the metallicities in the base.

use synthetic stellar libraries to correct the empirical stellar libraries (e.g. [52, 68, 4]).

4 Spectral synthesis: the fossil method

Instead of the common approach of using the index measurements to constrain the stellar population properties, here I show the advantages of using the spectral synthesis to derive the star formation history of galaxies. The strategy is to consider that the integrated light from a galaxy is the sum of simple stellar populations, each with its ages and metallicities; thus, the galaxy luminosity is calculated as:

$$L_\lambda^{\rm gal} = L_{\lambda_0}^{\rm gal} \sum_{j=1}^{N} x_j \gamma_{\lambda,j}^{\rm SSP}(t,Z) 10^{-0.4 A_V (q_\lambda - q_{\lambda_0})} \quad (1)$$

where x is a scaling factor, $q_\lambda \equiv A_\lambda / A_V$ is the reddening curve, and

$$\gamma_{\lambda,j}^{\rm SSP}(t,Z) = \frac{L_\lambda^{\rm SSP}(t,Z)}{L_{\lambda_0}^{\rm SSP}(t,Z)} \otimes G(v_\star, \sigma_\star) \quad (2)$$

gives the spectrum of an SSP of age t and metallicity Z normalized at λ_0, convolved with a gaussian filter centered at velocity $v_\star$ and with dispersion $\sigma_\star$. The $L_\lambda^{\rm SSP}(t,Z)$ spectra are taken directly from the evolutionary synthesis models.

Several interesting algorithms (e.g. Starlight: [12]; ULySS: [33]; VESPA: [60]; MOPED: [48]; STECMAP: [47]) have been proposed to find out the x_j values, and extinction that minimizes the residuals:

$$\chi^2 = \sum_\lambda \frac{(O_\lambda - L_\lambda^{\rm gal})^2}{\epsilon_\lambda^2} \quad (3)$$

where ϵ_λ is the error in the O_λ spectrum.

Figure 4 shows one example of how the method works for a stellar cluster, for which the stellar population is well reproduced by just one SSP. The fit is obtained with Starlight.

Note, that the result depends on the stellar population spectra models used as the base of the fit. Figure 3 shows the results obtained with different set of models. However, the general conclusion is that overall all the models are able to produce very good quality fits. But caveats and uncertainties associated to the different models and the method have been presented in [22] and [11]. The method is superior to the stellar index measurements to break the age-metallicity degeneracy, and to be applied to the spectra of galaxies with recent star formation. This is illustrated in Fig. 5 for the LIRG merger system IIZw96.

Finally, to illustrate the power of the method Fig. 6 shows the color-magnitude diagram of the CALIFA sample. CALIFA is a survey of ∼600 galaxies in the local universe that are being observing with PPAK/3.5m telescope at CAHA (http://www.caha.es/sanchez/legacy/oa/, IP. Sebastian Sánchez). One of the goals of the project is to study when and how the galaxies

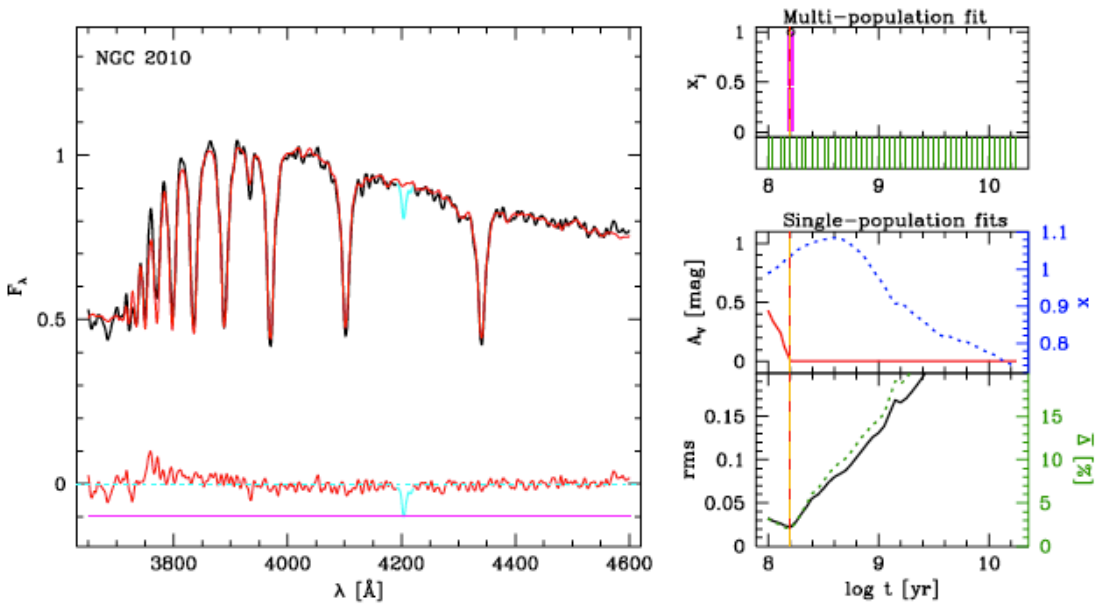

Figure 4: Starlight results for the LMC stellar cluster NGC 2210. Models are from [66]. Observed (black), best-fit (red) spectra and residual (bottom) are plotted on the left. Results of the multi-SSP fit is on the right. *Middle right*: Best fit A_V and x for single-SSP fits as a function of age. Solid (red) and dashed (orange) vertical lines mark the best single-SSP age and mean age in the multi-SSP fit. *Bottom right*: rms and $\overline{\Delta}$ figures of merit as a function of age.

evolve from the blue cloud to the red sequence. A first step in this topic can be achieved studying the average ages and metallicities of the galaxies, and how they distribute in the color-magnitude diagram. Using SDSS data and the archive results of Starlight for some of these galaxies (http://starlight.ufsc.br) we have confirmed that there is a good segregation of the galaxies in terms of the average weighted-light age and metallicity.

Acknowledgments

This work has been funded with support from the Spanish Ministerio de Educación y Ciencia through the grants AYA2007-64712, and co-financed with FEDER funds. Thanks to Enrique Pérez for doing the data reduction and the figure of IIZw96, to Roberto Cid and collaborators for making the SDSS fits results publicly available, to Miguel Cerviño, Enrique Pérez and Clara Cortijo for reading the paper. I am also very grateful to the organizers of the meeting for giving me the opportunity to present this talk.

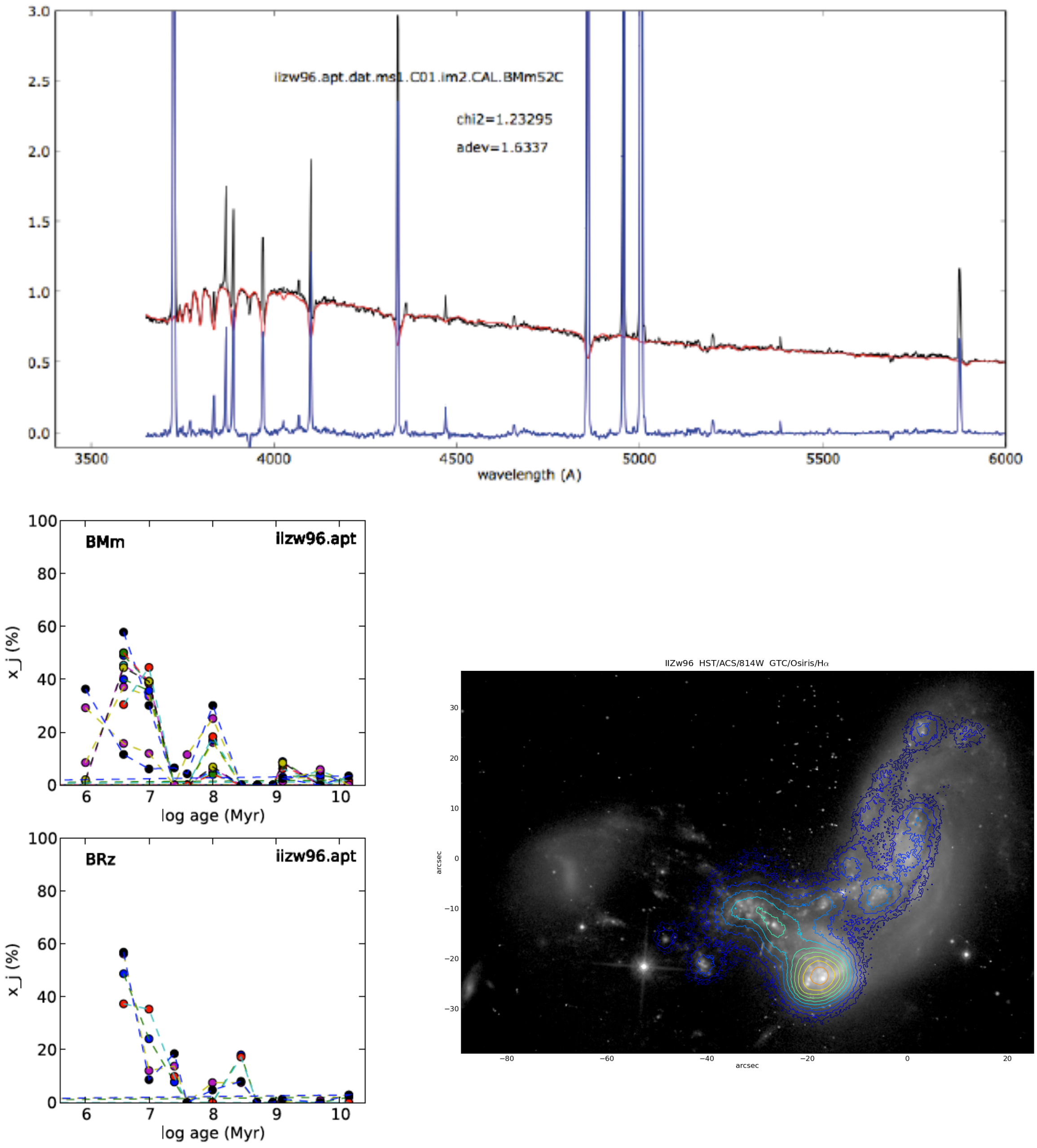

Figure 5: Starlight results for the merger LIRG IIZw96. *Up*: observed spectrum is in black, the best fit using the Charlot & Bruzual models is in red and at the bottom in blue is the residual spectrum. *Down left*: star formation history for IIZw96. The light is mainly provided by two components, a young ($\leq$ 10 Myr) plus an intermediate age population of $\sim$100 Myr. The results for different sets of models are plotted (lower panel: SSP from [26]; upper panel: SSP from [10]). *Down right*: HST/ACS image of the merger. In contours is the Hα emission observed with GTC/OSIRIS.

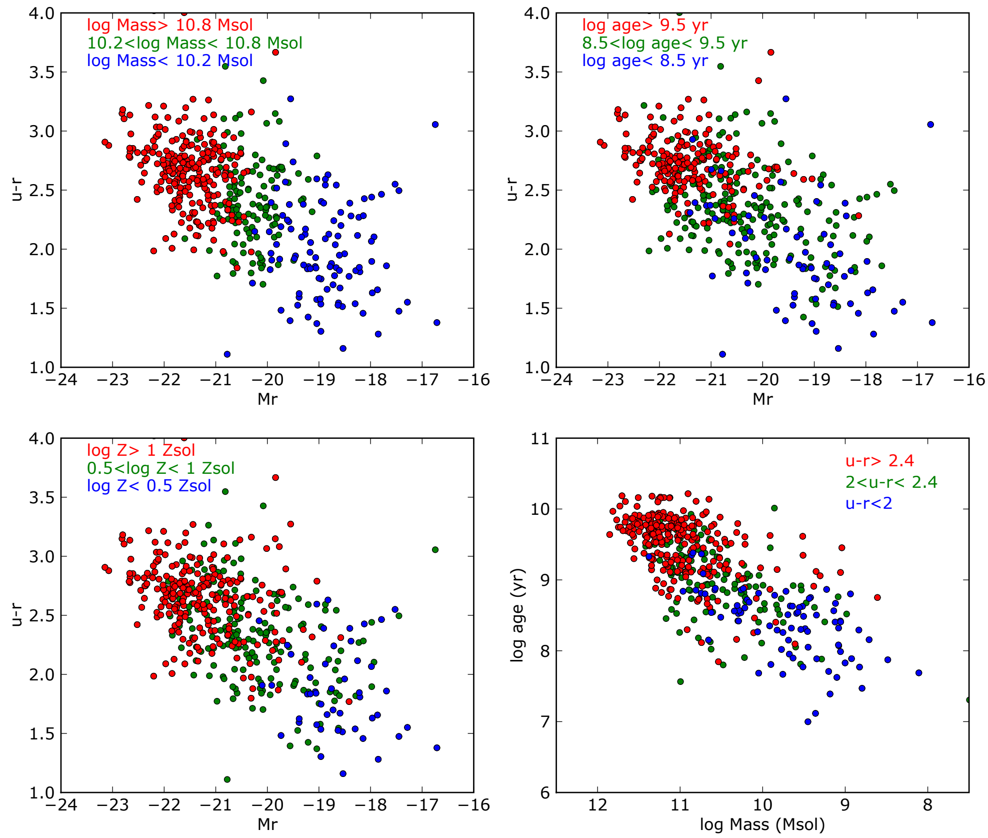

Figure 6: Color magnitude diagram for the sample of CALIFA for which SDSS spectra corresponding to a central aperture of 3 arcsec exists. The masses, ages and metallicities are obtained fitting the SDSS spectra with Starlight. The results were retrieved from the Starlight database http://starlight.ufsc.br. Note the segregation of the galaxies of different mass, age, and metallicity in the diagram.

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