Spectroscopic Dating of Stellar Populations from Local Star Clusters to Distant Galaxies and the Age of the Universe *

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I summarize in terms of evolutionary population synthesis models our current understanding of stellar populations in different environments, from star clusters in nearby galaxies to distant galaxies in clusters or seen through gravitational lenses. Constraints on the age of the stellar populations in clusters and galaxies derived from comparing predicted and observed spectral energy distributions are examined and contrasted with the maximum ages allowed by cosmological models at the corresponding redshift.

Keywords: galaxies: general, galaxies: evolution, galaxies: stellar populations

1. Introduction

Evolutionary population synthesis provides an important tool to study the stellar content of star clusters and galaxies as a function of age. The theory of stellar evolution makes definitive predictions concerning the bolometric luminosity and effective temperature of a star of a given mass and chemical composition. As time proceeds, the function describing the radial dependence of the chemical composition of the material inside the star varies, resulting in changes in the bolometric luminosity and the effective temperature characterizing a star of a given initial mass. The evolutionary track for this stellar mass is the line joining these successive points in the bolometric luminosity-effective temperature plane, known as the Hertzsprung-Russell diagram (HRD). Complete sets of evolutionary tracks for stars of a wide mass range and various initial metal contents covering all significant stellar phases are available in the literature (Fagotto et al. 1994a, b, c; Girardi et al. 2000). Assuming an initial mass function (IMF, e.g. Salpeter 1955), we can compute the number of stars of a given mass born at time zero, and then follow the evolution of this population in the HRD using a specific set of evolutionary tracks. Knowledge of the spectral energy distribution (SED) at each position in the HRD visited by the stars during their evolution, allows us to compute the integrated SED for this initial-burst or simple stellar population (SSP) as a function of time. By means of a convolution integral (Bruzual & Charlot 1993) the evolution of the SED can be computed for an arbitrary star formation rate (SFR) and a chemical enrichment law. A detailed description of the evolutionary synthesis technique has been published by Bruzual (1999). A discussion of the most important results obtained from spectral evolutionary models is also presented in this paper, as well as in Bruzual (2001a,b).

Several stellar spectral libraries are currently available. The Pickles (1998) atlas provides good coverage of the HRD for stars of solar metallicity \((Z_\odot)\) at medium spectral resolution. Recently, Le Borgne et al. (2002a) have compiled an equivalent atlas at 3Å spectral resolution (1Å sampling) which is complete for stars of solar metallicity, but includes a large number of spectra of non-solar metallicity stars. On the theoretical side the compilation by Lejeune et al. (1997, 1998) and Westera et al. (2002) provide libraries of model atmospheres for stars of various metallicities but at ≈20Å spectral resolution. The last two libraries are largely based on the Kurucz (1995) series of model stellar atmospheres.

In a parallel paper (Bruzual 2002), I have discussed the advantages of using a high resolution stellar spectral library, such as the Le Borgne et al. (2002a) atlas, in a set of evolutionary population synthesis models (Bruzual & Charlot 2002, BC02 hereafter). These models preserve the properties of models built at lower spectral resolution in what respects to integrated photometric properties of the stellar population, e.g. luminosity and color evolution, but achieve a much greater level of detail in reproducing the spectral features of the integrated population. This is particularly important when comparing model SEDs with observed spectra obtained with the high resolution spectrograph available in the Hubble Space Telescope (HST) and in the new generation of ground based high performance optical telescopes (Keck, VLT, Sloan). In this paper I show the results of

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Fig. 1: Comparison of the observed SED of the young massive cluster W3 in the galaxy NGC 7252 (kindly provided by F. Schweizer, heavy line) with a $Z = Z_\odot$ SSP at 0.57 Gyr computed for the Salpeter (1955) IMF using the Le Borgne et al. (2002a) stellar atlas (thin line). The model SED is the line extending to the extreme left and right in the plot.

comparing the predictions of the BC02 models with the observed SED of star clusters and galaxies seen at various cosmological epochs, as measured by their redshift ($z$).

2. Spectroscopic Age of Stellar Populations

In this section I use the BC02 models to derive the spectroscopic age that characterizes the observed SED of several sources at different distances from us. A model consists of a spectrum which evolves in time from age zero to 20 Gyr in 221 time steps. By minimizing $\chi^2 = \sum [\log F_\lambda(\text{observed}) - \log F_\lambda(\text{model})]^2$, we derive for each problem SED the (spectroscopic) age at which the model matches more closely the observed spectrum.

2.1. Star Clusters

Fig 1 shows a comparison of a BC02 model SED with the observed spectrum of the young massive (globular) cluster W3 in the galaxy NGC 7252, kindly provided by F. Schweizer. The model corresponds to a $Z = Z_\odot$ SSP at 0.57 Gyr computed for the Salpeter (1955) IMF using the Le Borgne et al. (2002a) stellar atlas. The spectra show a remarkable degree of agreement in the shape and intensity of the Hydrogen Balmer lines (H$_\beta$ through H14), the Mgb feature, the Fe and other lines indicated in the plot. The intensity of the Balmer lines is an excellent indicator of the age of the stellar population, provided that the spectral resolution of both spectra match in this wavelength range. This is the case in Fig 1. Models built with lower resolution libraries do not constrain the age of the cluster population so accurately.

2.2. Nearby Galaxies

In Fig 2 I show a VLT spectrum of an elliptical galaxy at $z = 0.142$ (kindly provided by J.-F. Le Borgne) in the field of the cluster of galaxies AC114 together with a BC02 model that produces the best match to the observed SED at an age of 12 Gyr. The model is the same one shown in Fig 1, but seen 11.43 Gyr later in its passive evolution. Many of the spectral features seen in the problem galaxy SED are real since they are also present in the stellar spectra used to build the model.

2.3. Intermediate Distance Galaxies

Stockton (2001) has identified galaxies dominated by old stellar populations at moderately high redshifts ($z \approx 1.5$). Presumably, these galaxies formed most of their stars early in the history of the universe and have evolved passively later on. The data
Fig. 2: VLT spectrum of an elliptical galaxy at $z = 0.142$ gravitationally lensed in the field of the cluster of galaxies AC114 (kindly provided by J.-F. Le Borgne, heavy line) compared with the same model of Fig 1 but seen at 12 Gyr (thin line).

Fig. 3: Broad band photometry in the galaxy rest frame for LBDS 53W091 and six galaxies from Stockton’s sample compared to the model of Fig 1 at the age indicated in each panel (thick line). The 1.4 Gyr SED is repeated in all the frames (thin line) to guide the eye.

points in the different frames of Fig 3 show the broad band photometry in the galaxy rest frame for LBDS 53W091 (Spinrad et al. 1997), and six galaxies from Stockton’s sample. The colors or broad band fluxes of LBDS 53W091 are well reproduced by the same solar metallicity, Salpeter IMF, BC02 model SSP introduced above at an age of 1.4 Gyr (top frame on the left hand side in Fig 3; see also Bruzual & Magris 1997). Two of the galaxies observed by Stockton have the colors of this population at 2 Gyr, whereas the remaining 4 galaxies seem older, $\approx 4Gyr$. The 1.4 Gyr SED is repeated in all the frames as a guide to the eye in establishing the differences between the SEDs. Despite the photometric errors and the intrinsic uncertainties in the population synthesis technique, it seems safe to conclude that even though these 7 galaxies are at very similar redshifts, their stellar populations differ in age by a factor of two. This may give us an indication on how precisely tuned star formation was at the time of formation of these galaxies.

2.4. Distant Galaxies. A Passive Evolution Sequence

Fig 4 shows in a concise way a comparison of the predicted passive evolution of the SED of a SSP at 6 different epochs and observations (either broad band fluxes and/or SEDs) of various galaxies covering a wide range in redshift space. The age of the model that reproduces the observations is indicated in each panel. At one age extreme, object S2 in the top panel of Fig 4, a young (6 Myr) reddened starburst at $z = 1.87$ seen through a gravitational lens (Le Borgne et al. 2002b), provides an example of a very young population at a cosmological epoch at which (elliptical?) galaxies dominated by old populations were already in place. Object H5 (Pelló et al. 1999), shown in the second panel of Fig 4, at $z = 4.05$ is a quite distant galaxy also seen through a gravitational lens and is characterized by a stellar population with age close to 60 Myr. Source 3 by Cowie et al. (2001) at $z = 2.6$ is another lensed galaxy seen at an age close to an order of magnitude older than object H5. M32 and an average nearby elliptical galaxy SED, shown in the two bottom panels in Fig 4, characterize present day local counterparts of the spectral energy distribution of old stellar populations. LBDS 53W091 (Fig 3), reproduced in the 4th panel of Fig 4, provides a link between the younger and older than 1 Gyr stellar populations. Fig 4 thus shows a plausible evolutionary sequence of elliptical galaxy spectra.
3. Spectroscopically Dated Galaxies and the Age of the Universe

Fig 5 shows the age of the universe as a function of redshift for two different cosmological models. The data points represent the ages determined spectroscopically for the different galaxies shown in Figs 3 and 4, as well as globular star clusters taken from the literature. It is clear that the age of local E galaxies and globular clusters, and possibly LBDS 53W091 and two of Stockton’s galaxies, rule out the $H_0 = 70$ km s$^{-1}$ Mpc$^{-1}$, $\Omega_M = 1$, $\Omega_\Lambda = 0$ universe with a maximum age $t_U(0) = 9.33$ Gyr at $z = 0$ (bottom solid line). On the other hand, the age of these systems and of all galaxies shown in Fig 5, is below the age($z$) line for the standard model, $H_0 = 70$ km s$^{-1}$ Mpc$^{-1}$, $\Omega_M = 0.28$, $\Omega_\Lambda = 0.72$, $t_U(0) = 13.75$ Gyr (top solid line). A selection effect is clear in Fig 5, the sources that have been observed, except for the galaxies at $z \approx 1.55$, represent the youngest, and possibly the brightest galaxies at a given $z$, and may not be representative of the galaxy population as a whole in that shell of $z$-space. Equally young stellar populations seem to be present at all $z$’s, at least from $z \geq 2$ to $z \leq 4$.

4. Discussion

I have shown how evolutionary population synthesis models can be used to assign a spectroscopic age to stellar populations whose SED or multi-broad-band photometry is available. The error in the age determination depends on the quality of the observational data and on the uncertainties in the population synthesis models. In general, the relative error in the spectroscopic age increases with decreasing galaxy age. Despite this caveat, it is possible to establish a plausible sequence along which the spectra of galaxies may evolve when passive evolution dominates the evolution of simple stellar populations, at a rate that is consistent with that expected in the most accepted cosmological model describing our universe, $H_0 = 70$ km s$^{-1}$ Mpc$^{-1}$, $\Omega_M = 0.28$, $\Omega_\Lambda = 0.72$, $t_U(0) = 13.75$ Gyr.
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