RevMexAA (Serie de Conferencias), **24**, 129–138 (2005)

ABSORPTION LINE INDICES FOR STUDYING STELLAR POPULATIONS

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RESUMEN

Las intensidades de líneas de absorción nos han permitido llevar a cabo análisis muy completos de poblaciones estelares al proporcionar fuertes restricciones para discriminar y limitar los actuales escenarios de formación de galaxias. Describo las principales características de este enfoque, señalando los índices y diagramas de diagnóstico más populares y también los principales problemas que afectan estos estudios, tales como la degeneración entre metalicidad y edad. Se hace especial énfasis en los esfuerzos para definir los diagnósticos con mayor precisión; esto nos permitiría explotar plenamente el flujo de datos de alta calidad obtenidos gracias a la actual generación de grandes telescopios, incluyendo el GTC.

ABSTRACT

Absorption line-strengths have allowed us to carry out a comprehensive stellar populations analysis, providing very strong constraints for discriminating and constraining current galaxy formation scenarios. I describe the main features of this approach, pinpointing the most popular indices and diagnostic diagrams, and the main problems affecting these studies such as the age-metallicity degeneracy. A special emphasis is given to ongoing efforts aiming at defining more accurate diagnostics, which allow us to fully exploit the flow of high quality data from current generation of large telescopes, including GTC.

Key Words: **GALAXIES: STELLAR CONTENT — STARS: ATMOSPHERES**

1. INTRODUCTION

There are two competing scenarios for explaining how galaxies form and evolve. According to the monolithic collapse model galaxies form rapidly in a single structural process (Eggen, Lynden-Bell & Sandage 1962; Larson 1974). In Lambda Cold Dark Matter cosmology a galaxy form when gas reaches high enough densities to cool, sink to the center of a high density lump of dark matter, and form stars. Gravity causes galaxy clumps to merge with each other as their surrounding dark matter halos coalesce and the gas is compressed forming new stars (Press & Schechter 1974; White & Frenk 1991). According to this scenario these merger events may extend to z$\sim$1 for most massive galaxies (e.g., Baugh, Cole & Frenk 1996; Kauffmann & Charlot 1998a,b). There has been a recent paradigm shift to this scenario as many observed structural and dynamical properties of galaxies in clusters are properly accounted for in this model, though problems remain such as the prediction of far more satellite galaxies than those observed.

These scenarios can be constrained by studying the stellar populations, which represent a fossil record of galaxy star formation history and chemical evolution. Particularly relevant is the study of early-type galaxies (ellipticals and lenticulars), thought to have formed from merging of discs, which represent more than the half of the total stellar mass of the universe (e.g., Gray et al. 2004; Smith et al. 2004). It turns out that the results obtained from stellar population studies are in tension with the hierarchical galaxy formation framework. It is for example difficult to reconcile this scenario with the fact that early-type galaxies satisfy a number of tight scaling relations such as the Fundamental Plane (Djorgovski & Davis 1987; Dressler et al. 1987) or the Color-Magnitude Relation, CMR (Bower et al. 1992; Colless et al. 1999). Furthermore a tight CMR has been recently found at z=1.24 (Blakeslee et al. 2003). Red galaxies, e.g., EROS (e.g., Moustakas et al. 2004), and luminous sub-mm galaxies (e.g., Chapman et al. 2003) are found at very high z. It has been recently found that larger galaxies show larger mean ages than the smaller ones (Kauffmann et al. 2003; Caldwell, Rose & Concannon 2003). Furthermore, nearby giant elliptical galaxies show [Mg/Fe] overabundance (e.g., Worthey et al. 1992; González 1993). All these evidences suggest that the bulk of the stars of massive early-type galaxies were formed at very early times, in apparent contradiction with current hierarchical picture as predicted from semi-analytic modeling (Baugh, Cole & Frenk 1996; Kauffmann & Charlot 1998a; Cole et al. 2000).

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Deriving most relevant stellar population parameters, such as ages and metallicities, require to compare observed colors or absorption line-strengths to the predictions of the so called stellar population synthesis models. However, the study of the integrated light of a stellar system suffers from a number of problems, such as the age/metallicity degeneracy, which makes a galaxy to look redder either because it is older or more metal rich (O'Conell 1986; Worthey 1994; Arimoto 1996). Other problems such as our difficulties for disentangling the effects of the Initial Mass Function, IMF (Vazdekis et al. 2003), or the degeneracy between the age of a burst and its strength (Leonardi & Rose 1996), making the interpretation significantly more uncertain. Due to these limitations it is more plausible to determine galaxy mean-luminosity weighted ages and metallicities, rather than attempting to retrieve galaxy true star formation histories. These mean luminosity weighted stellar population parameters are obtained by comparing the observations to the predictions of single burst models. Therefore the derived age do not necessarily reflect the age of the oldest stars in a galaxy, but it emphasizes any contribution from younger, i.e. brighter, stellar components.

The inclusion of absorption line-strengths in the stellar population analysis provides us with larger abilities for breaking these degeneracies. Line-strengths provide selective information on the abundances of several elements. Another advantage is that line-strengths are mostly free from dust effects, which redden the colors. On the other hand this approach requires high signal-to-noise (S/N) spectra, which in general require telescopes of mirror diameters larger than ∼3m. In fact in the last decade line-strength studies did not reach galaxy effective radii, and most of these studies focused on galaxies of the nearby universe. Another important limitation of the line-strength studies is that long-slit spectroscopy, i.e. the most common technique employed so far, only allows us to obtain information from just one or few spatial directions of a given galaxy.

This review is organized as follows. Section 2 summarizes the most popular absorption line-strength indices, including the main characteristics of the very popular Lick/IDS system. The model predictions are described in Section 3. Section 4 illustrates with some examples the power of the line-strength studies for constraining galaxy formation scenarios. Section 5 investigates the possibilities of improving the line-strengths method for exploiting higher quality data from the new generation of 8-10m class telescopes. Finally a summary with some general conclusions are given in Section 6.

2. ABSORPTION LINE-STRENGTHS

The Lick/IDS system (Burstein et al. 1984; Gorgas et al. 1993; Worthey et al. 1994; Worthey & Ottaviani 1997) is the most popular set of indices employed so far (see the compilation of Trager et al. 1998). This system, which is composed of 25 indices from CN at ∼4150 Å to $\mathrm{TiO_2}$ at ∼6200 Å, is based on ∼450 stars that were appropriately selected to cover a wide range of stellar atmospheric parameters ($T_{\rm eff}$, logg, [Fe/H]). The definition of a Lick-style index includes a central bandpass bracketed by two pseudocontinua bandpasses, which are used to draw a straight line to determine the continuum level at the feature. Atomic features (e.g., Hβ, Mgb, Fe5270, Fe5335) are expressed in units of Angstroms and are defined as follows:

$$\mathrm{EW} = \int_{\lambda_1}^{\lambda_2} \left(1 - \frac{F_I}{F_C}\right) d\lambda \qquad (1)$$

where F_I and F_C are the fluxes per unit wavelength in the index passband and the straight-line continuum flux in the index passband respectively.

Molecular bands (CN1, CN2, $\mathrm{Mg_1}$, $\mathrm{Mg_2}$, $\mathrm{TiO_1}$, $\mathrm{TiO_2}$), which are expressed in magnitudes, are defined according to the expression:

$$\mathrm{Mag} = -2.5 \log \left[\left(\frac{1}{\lambda_2 - \lambda_1} \right) \int_{\lambda_1}^{\lambda_2} \frac{F_I}{F_C} d\lambda \right] \qquad (2)$$

Atomic indices usually depend on the spectral resolution, or galaxy velocity dispersion, but show little sensitivity to the spectrum shape. However the molecular bands (CN1, CN2, $\mathrm{Mg_1}$, $\mathrm{Mg_2}$, $\mathrm{TiO_1}$, $\mathrm{TiO_2}$) do not depend on the spectral resolution but show significant sensitivity to the spectral response curve. The major drawbacks of the Lick/IDS system are discussed in detail in Worthey & Ottaviani (1997). Among other problems, the spectral resolution of the observed stellar spectra vary as a function of wavelength (FWHM ∼11 Å around 4000 Å to ∼8.5 Å around 5000 Å). Moreover, since the stellar spectra were not flux-calibrated their spectral energy distributions (SEDs) are affected by the response curve of the Lick/IDS spectrograph.

Alternatively, the system of indices introduced by Rose (1985, 1994) is meant to work at significantly higher spectral resolution. These indices, which include information from more species, measure the relative central line depths of two neighboring features without taking into account the continuum. In fact, this independence on the location of the continuum is an advantage over the Lick-style indices. On the other hand these indices show large sensitivity to the spectral resolution and to the S/N (Vazdekis 2001).

There are other popular indices such as e.g., the 4000 Å break (Bruzual 1983; Gorgas et al. 1999; Balogh et al. 1999), the near-IR CaII triplet at ∼8600 Å (e.g., Díaz, Terlevich & Terlevich 1989; Cenarro et al. 2001a) or the CO at 1.6 and 2.3 μm (e.g., Kleinmann & Hall 1986; Frogel et al. 2001). These indices provide valuable information from different spectral ranges, which are dominated by different stellar spectral types.

3. LINE-STRENGTH MODEL PREDICTIONS

Relevant stellar population parameters are obtained by comparing data to the predictions of the stellar population synthesis models. Basically, these models combine our current knowledge on stellar evolution theory with stellar spectral libraries and assume an IMF to predict SEDs of single-age single-metallicity stellar population, SSPs, or more complex stellar populations with different star formation histories or/and chemical evolutions. Therefore the main ingredients of these models are a set of theoretical isochrones for different ages and metallicities (e.g., Girardi et al. 2000; Salaris, Groenewegen & Weiss 2000; VandenBerg et al. 2000; Yi et al. 2003; Pietrinferni et al. 2004) and stellar spectral libraries, either theoretical (e.g., Kurucz 1992; Lejeune, Cuisinier & Buser 1998,1999; Hauschildt et al. 1999a,b; Bertone et al. 2004; Zwitter et al. 2004; see also Chavez, this volume) or empirical (e.g., Díaz, Terlevich & Terlevich 1989; Gorgas et al. 1993; Worthey et al. 1994; Pickles 1998; Jones 1999; Cenarro et al. 2001a; Le Borgne et al. 2003).

Stellar population synthesis models predict photometric properties such as colors, mass-to-light ratios, surface brightness fluctuations (e.g., Arimoto & Yoshii 1986; Bruzual & Charlot 1993; Bressan et al. 1994; Worthey 1994; Buzzoni 1995; Vazdekis et al. 1996; Kodama & Arimoto 1997; Maraston 1998; Blakeslee et al. 2001; Liu, Charlot & Graham 2000; Yi 2003), SEDs at very low resolution (e.g., Bruzual & Charlot 1993; Bressan et al. 1994; Kodama & Arimoto 1997), a number of line-strengths, mostly on the Lick/IDS system (e.g., Worthey 1994; Vazdekis et al. 1996; Maraston et al. 2003) and, more recently, SEDs at moderately high resolution (Vazdekis 1999; Schiavon et al. 2002; Bruzual & Charlot 2003; Vazdekis et al. 2003).

3.1. *Predicting integrated line-strengths on the Lick/IDS system*

The key ingredients for predicting line indices at low spectral resolution, particularly those of the Lick/IDS system, are the empirical fitting functions, which relate the index strengths to the stellar atmospheric parameters ($T_{\rm eff}$,log g,[Fe/H]) of the Lick stellar library (Gorgas et al. 1993; Worthey et al. 1994; Worthey & Ottaviani 1997). There are alternative fitting functions such as the ones of Buzzoni, Mantegazza & Gariboldi (1994) or Idiart, Thévenin & Freitas-Pacheco (1997). To obtain a line-strength of a stellar population the predicted index value for each star is integrated along the isochrone. For this integration the stellar index is weighted according to the luminosity of the continuum corresponding to the wavelength interval of the feature, and multiplied by the number of stars as derived from the assumed IMF.

To be able to use these model predictions the observed galaxy spectrum should be smoothed to match the wavelength dependent resolutions of the Lick/IDS system, and data must be adapted to the response curve of the Lick/IDS spectrograph. Finally a correction from galaxy velocity dispersion should be applied to bring the data to the resolutions of the Lick/IDS system (see Section 2). These steps require observing a sample of Lick stars with the same instrumental configuration used for obtaining galaxy spectra. Various diagnostic diagrams can be used for interpreting the observations, such as plotting an age-sensitive indicator, e.g. Hβ, against various metallicity-sensitive indicators (e.g., Mg_2, Fe5270, Fe5335) to partially lift the age/metallicity degeneracy. However the most popular age indicator, Hβ, is not free from metallicity effects and it might be affected by nebular emission (González, this volume).

These predictions, which require to adapt the observed galaxy spectra to the models, are not optimal for exploiting the data flow from current generation of large telescopes, which provide spectra of greater qualities than the models.

3.2. *Spectral synthesis at higher resolution*

New empirical stellar spectral libraries with flux-calibrated spectral response, and much improved atmospheric parameter coverage, have allowed us to predict integrated SEDs at moderately high resolution, rather than predicting a number of line-strengths at low resolution. Vazdekis (1999) and Schiavon et al. (2002) predict SEDs in two narrow spectral ranges around 4000 Å and 5000 Å at resolution 1.8 Å (FWHM). These models employ the library of Jones (1999), which is composed of more than 600 stars. Vazdekis et al (2003) employs the library of Cenarro et al. (2001a,b), which is composed of ∼700 stars, to predict SSP spectra in the CaII triplet region around 8500 Å at resolution 1.5 Å (FWHM). Finally the models of Bruzual & Charlot (2003) predict SEDs in the range $\lambda\lambda$ 3500 − 9000 Å at resolution 3 Å (FWHM), employing the library STELIB (Le Borgne et al. 2003), which include ∼250 stars.

These new predictions introduce a new methodology for analyzing spectra of galaxies and stellar clusters (Vazdekis 1999). First the resolution and dispersion of the synthetic spectra are adjusted to match the instrumental configuration used for the observations. Second, the model spectra are smoothed to match galaxy velocity dispersion. Finally, the synthetic spectra can either be compared to the whole spectrum (or part of it) or the comparison can be made on the basis of selected line-strengths, which are measured in both the observed and synthetic spectra.

3.3. *Dealing with abundance ratios*

Line-strength model predictions are based on stellar libraries obtained in the solar neighborhood. Therefore their intrinsic abundance ratios follow a scaled solar pattern (for stars with metallicities close to solar). However giant early-type galaxies show non solar abundance ratios such as [Mg/Fe]>0 (e.g., Worthey et al. 1992). Several alternatives have been proposed to deal with this problem. The most popular approach is to use models specifically computed for different abundance ratios (e.g., Tantalo, Chiosi & Bressan 1998; Trager et al. 2000a; Thomas, Maraston & Bender 2003a; Thomas & Maraston 2003). These models take into account the sensitivities of these lines to the abundance changes of the different species as tabulated in (Tripicco & Bell 1995). The second approach relies on isochrones specifically computed for different α-enhancements (Salaris & Weiss 1998; Salasnich et al. 2000; Kim et al. 2002; VandenBergh et al. 2000). For high metallicities these isochrones cannot be mimicked by scaled-solar isochrones of the same total metallicity (e.g., Salaris & Weiss 1998). However, predicted line-strengths are based on the same empirical fitting functions used for the standard model predictions, i.e. with scaled-solar ratios. Note that neither the first approach nor the second is fully self-consistent as the same abundance pattern should apply for both, the stellar interiors and the stellar atmospheres. Finally, the third approach relies, exclusively, on scaled-solar model grids. Here the strengths of several metal line indices, which are mostly dominated by specific species, are plotted versus an age indicator, which shows very little dependence on metallicity. Since the resulting model grids are virtually orthogonal, we can estimate galaxy mean ages and the metallicities obtained from these metallic indices. For a given galaxy the obtained metallicities will be different if the galaxy shows a departure from scaled-solar element ratios as in the models. Since these metallic indices are by far dominated by specific elements, the obtained metallicities can be approximated to the corresponding abundances. These values are then used to estimate the abundance ratios (Vazdekis et al. 2001).

4. RESULTS

This section shows a number of results that have been selected to illustrate the potential of the line-strength studies for constraining galaxy formation scenarios. By no means this section aims to be complete, showing all relevant results that have been obtained so far. The reader can find a larger number of references in, e.g., Trager et al. (1998), Terlevich & Forbes (2002).

Early-type galaxies show a well known relation between the Mg_2 index and the velocity dispersion (e.g., Bender et al. 1992; Colless et al. 1999). The CMR and the $\mathrm{Mg}_2 - \sigma$ relations link the mass of a galaxy, through its luminosity, to its constituent stellar populations. The most popular interpretation is that these relations are the result of a metallicity sequence. However it has been pointed out that the main feature driving these relations is the fact that larger galaxies show larger departures from solar [Mg/Fe] ratio (e.g., Vazdekis et al. 2001). Very short formation timescales for massive ellipticals are claimed for explaining the [Mg/Fe] overabundance (e.g., Worthey et al. 1992). The magnesium, which is an α-element, is ejected into the ISM by Type II supernovae (SNe II) on very short timescales (<10 Myr), whereas the iron-peak elements are released by SNe Ia, which occur on timescales of ∼1 Gyr. Alternatively, it has been proposed a time variation of the IMF for explaining the [Mg/Fe] overabundance. According to this scenario the IMF was skewed toward massive stars at very early epochs, either due to a lower mass cutoff (e.g., Elbaz et al. 1995) or a flatter IMF (e.g., Vazdekis et al. 1997).

Another important result, which is at odds with the standard hierarchical paradigm, is the recent finding that larger galaxies show larger mean luminosity weighted ages than their smaller counterparts.

This has been shown on the basis of a sample of 10^5 galaxies from the Sloan Digital Sky Survey (Kauffmann et al. 2003), and from smaller galaxy samples with much higher S/N spectra (e.g., Caldwell, Rose & Concannon 2003; Yamada et al. 2004, in preparation).

A result supporting the hierarchical model predictions is that ellipticals in lower density environments show larger age dispersion than cluster ellipticals (e.g., Trager et al. 2000a,b; Kuntschner et al. 2002). Perhaps a related result is that lenticular galaxies show larger age scatter than ellipticals in the Fornax cluster (Kuntschner & Davies 1998). However, the present observational base is small as detailed stellar population analyzes have only been performed on three clusters: Virgo (e.g. Vazdekis et al. 2001), Fornax (e.g. Kuntschner 2000) and Coma (e.g. Jørgensen 1999).

Differences in the abundances of C and N as a function of environment have been recently reported by Sánchez-Blázquez et al. (2003). Furthermore, Carretero et al. (2004) find a clear trend between the [Mg/CN] and [CN/Fe] abundances measured in intermediate and massive early-type galaxies and cluster X-ray luminosity. This is interpreted given varying formation timescales for CN, Mg and Fe, suggesting that early-type galaxies in more massive clusters are assembled on shorter timescales than those galaxies within less massive clusters. Although this idea is supported by semi-analytic models, there is a severe quantitative disagreement as the involved time scales are significantly shorter than those predicted by these models.

A puzzling result is that Ca is low with respect to the values predicted by standard models based on scaled-solar ratios and Salpeter (1955) IMF. This has been shown on the basis of the Ca 4227 line (Vazdekis et al. 1997; Peletier et al. 1999; Vazdekis et al. 2001) and on the near-IR Ca_{II} triplet feature around 8600 Å (Saglia et al. 2002; Cenarro et al. 2003; Falcón-Barroso et al. 2003a; Michielsen et al. 2003). Furthermore the latter is the first metallic index that decreases with galaxy mass. Calcium underabundance or a steeper IMF have been proposed as possible explanations (e.g., Cenarro et al. 2003; Thomas et al. 2003b). However non of these possibilities are fully consistent with other observational constrains.

Line-strength studies are becoming increasingly popular for analyzing stellar populations in extragalactic globular cluster systems, for which detailed Color-Magnitude Diagrams of their resolved stellar populations cannot be obtained. These studies have not only confirmed a bimodal metallicity feature, previously reported by photometric studies, but have also shown differences in their abundance ratios (e.g., Larsen et al. 2003; Beasley et al. 2004).

Absorption line-strengths have also been measured in high redshift galaxies. For example, the Sloan Digital Sky Survey have obtained spectra of hundreds of thousands of galaxies out to z∼0.3 (e.g., Bernardi et al. 2003). Line-strengths were measured at even higher redshifts (e.g., Kelson et al. 2001, van Dokkum et al. 2003). Kelson et al. have shown no significant age scatter increase from z=0 to z∼0.8.

5. LINE-STRENGTHS IN THE ERA OF LARGE TELESCOPES

This section describes some of the major challenges and perspectives of the stellar population analysis in the context of the current generation of 8-10m class telescopes, which are already providing data of very high quality. Indeed models are catching up with data, rather than data catching up with models. Furthermore the methods for obtaining relevant stellar population parameters should be improved. Fig. 1 illustrates how the obtained ages depend on the selected diagnostic diagrams.

The newly synthesized model SEDs at moderately high resolution (Vazdekis 1999; Schiavon et al. 2002; Bruzual & Charlot 2003) allow us to investigate new indicators with greater abilities to disentangle the fundamental degeneracies affecting the integrated light of the stellar systems. Thanks to these models Vazdekis & Arimoto (1999) proposed a new age indicator, $\mathrm{H}\gamma_\sigma$, which is virtually free from metallicity effects for intermediate and old aged stellar populations. When this index is plotted versus different metallicity indicators we obtain virtually orthogonal model grids that allow us to separate ages and metallicities (Vazdekis et al. 2001). This is illustrated in Fig. 2 where the estimated ages do not depend on the metallicity indicator in use.

Separating the strength of a burst from its age is a mandatory step that is required for estimating galaxy star formation histories. Leonardi & Rose (1996) showed that the CaII index, defined as the ratio of the residual central intensities of neighboring spectral features CaII H+H_ϵ and CaII K lines (Rose 1985,1994), is very sensitive to the presence of intermediate aged stellar populations (younger than ∼1.5 Gyr). Along these lines, absorption line-strengths can also be helpful for detecting young starburst episodes, such as the near-IR CaII triplet feature (Mayya 1997).

These new indicators do not necessarily have to follow a Lick-style index definition, i.e. a feature

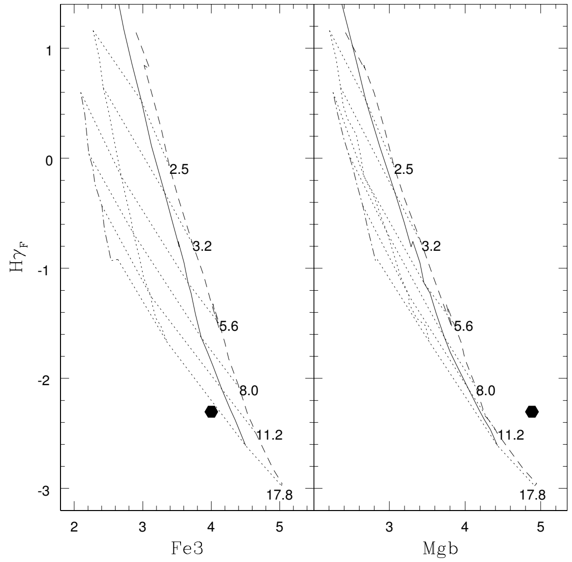

Fig. 1. The Hγ_F age indicator of Worthey & Ottaviani (1997) is plotted versus Fe3 (Kuntscher 2000) and Mg*b* (Worthey et al. 1994). The model grid of Vazdekis (1999) is overplotted: thick lines indicate constant metallicities [Fe/H] = −0.7 (dot-dashed), −0.4 (dotted), 0.0 (solid) and +0.2 (dashed lines). Thin dotted lines mean constant ages (quoted in Gyr). The observed values correspond to the elliptical galaxy NGC 4473 (Vazdekis et al. 2001a). Note that the inferred age is much larger when the Fe3 index is used as a result of the [Mg/Fe] overabundance of this galaxy.

bandpass bracketed by two pseudocontinua bandpasses. For example, Cenarro et al. (2001a) introduced the generic indices, which include multiple features and pseudocontinua bandpasses. Following this approach Cenarro et al. defined a new CaII triplet at ~8600 Å, CaT*, which is free from contamination of the Paschen series. The CaT* index shows a great ability to disentangle the effects of the IMF for old and metal-rich ([M/H]>-0.5) stellar populations (Vazdekis et al. 2003).

It is very important to extend these studies to other spectral regions that are dominated by different stellar spectral types. For example, the CO band-heads at 1.6 and 2.3 μm are promising candidates for disentangling the IMF (Frogel et al. 1984). These indices have already been measured in nearby elliptical galaxies (e.g., James & Mobasher 2000; Mobasher & James 2000). However, there is a lack of line-strength model predictions in this spectral range. For this purpose new empirical stellar libraries covering these spectral ranges are required (Ivanov et al. 2003; see also Gorgas and Mármol et al., this volume).

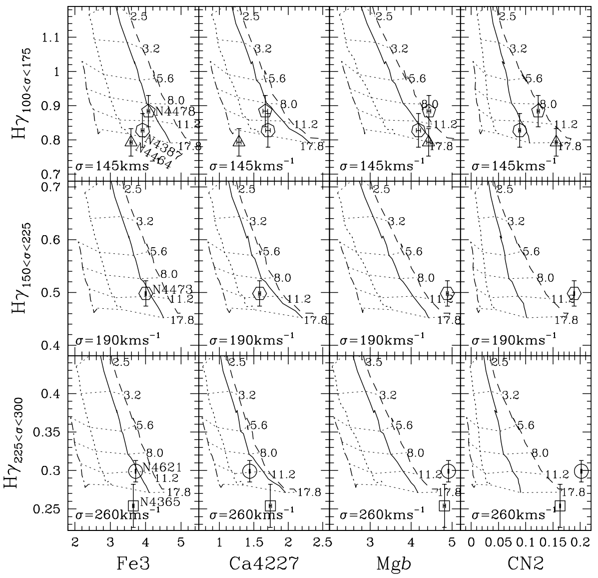

Fig. 2. The Hγ_σ age indicator of Vazdekis & Arimoto (1999) plotted vs. different metallicity indicators. Overplotted are the models of Vazdekis (1999) with line types as in Fig. 1. The panels show an unprecedented power to break the age-metallicity degeneracy (lines are essentially orthogonal). Very high S/N data of six Virgo elliptical galaxies selected along the CMR of the this cluster are shown: low luminosity with low velocity dispersion ($\sigma \sim 135 km/s$) galaxies on the top panels, in the center a galaxy with $\sigma = 180 km/s$ and in the bottom the more luminous galaxies ($\sigma \sim 255 km/s$). The metallicity, as measured by Mg or CN indices, increases along the CMR, whereas the Fe or Ca, show a modest increase from the top to the bottom panels. From Vazdekis et al. (2001a).

Most of the line-strength studies that have been performed so far are based on long-slit spectroscopy. Very important advances in this field are being obtained with Integral Field Units (IFUs). For example the SAURON spectrograph, which is attached to the William Herschel Telescope (4.2m), have provided index maps that allow us to study, e.g. line-strength gradients in great detail as well as the relation between the stellar populations and kinematic properties (e.g., Davies et al. 2001). Determining the origin of line-strength gradients is extremely important for constraining galaxy formation scenarios (e.g., González & Gorgas 1996; Kobayashi & Arimoto 1999). Unfortunately a major limitation of current IFU facilities is their small field of views. An alternative and promising approach, which is particularly relevant for GTC, is shown by Cervantes et al. (this volume). New indicators are modeled on the basis of the Tunable Filters of OSIRIS (Day

One instrument of GTC). These filters, which may reach a resolution of ∼5 Å (FWHM), are positioned on a particular feature and on selected pseudocontinua, making use of the charge-shuffling technique. This approach allows us to obtain full images of selected indices. This approach allows us to reach fainter galaxies that cannot be observed with spectroscopic methods. Moreover, for nearby galaxies selected line-strengths can be measured out to 3-4 times galaxy effective radii.

It is worth noting that a promising application of these model SEDs for determining the kinematics of galaxies is emerging. This has been possible by means of optimal model template fitting, which removes the well known template mismatch problem affecting all kinematical algorithms (e.g., Tonry & Davis 1979; Rix & White 1992; Kuijken & Merrifield 1993; van der Marel & Franx 1993). The newly synthesized SSP spectra provide as good or better fits than traditional stellar or mix of stellar templates, including the higher order Gauss-Hermite moments (Falcón-Barroso et al. 2003b). This approach has been developed by the SAURON team (Cappellari & Emsellem 2004) to separate and study the kinematics of both the stellar and gaseous components (which might be filling in the Hβ line).

Line-strengths allow us to reach a step further in the analysis of resolved stellar populations. We have started to obtain spectra of individual stars of galaxies that belong to the Local Group (e.g., Côté, Oke & Cohen 1999; Shetrone et al. 2001,2003; Cole, Smecker-Hane, T. A., & Gallagher 2000; Tolstoy et al. 2001; Kaufer et al. 2004; Venn et al. 2003). The abundances of several tens of elements that can be obtained from such spectra provide strong constraints on galaxy evolution models, and serve as important clocks on the timescales of galaxy formation, through the abundances of key chemical species. This approach is complementary to the standard CMD studies. Moreover, these observations should allow us to rigorously compare the results obtained from the analysis of resolved stellar populations with those obtained from the integrated light, with the aim of providing the latter with robust calibrations.

6. SUMMARY

Absorption line-strengths represent a powerful tool for disentangling most relevant stellar population parameters. In the last decade important advances have been achieved on the basis of these studies such as the Mg $-$ σ relation, the [Mg/Fe] overabundance of intermediate and massive early-type galaxies, or the departure from solar ratios of other species. These studies have provided very strong constrains for constraining the current galaxy formation paradigm. From a stellar populations point of view most of these studies suggest that the best hierarchical model is the one that looks more monolithic.

It is clear that the current generation of 8-10m class telescopes, such as GTC, will dedicate an important fraction of the observing time to this type of projects. The potential of line-strengths has also been shown to be useful for studying galaxies at higher redshifts. New instruments, such as multi-object spectrographs are making it much easier to complete surveys of millions of objects up to large distances and look-back times. Integral field spectrographs are revolutionizing the spectroscopy, providing a more complete view of nearby galaxies, which include their stellar population and kinematic properties. Along these lines it is particularly relevant for GTC the potential of the tunable filters of its Day One instrument OSIRIS.

With the new generation of models predicting full SEDs at moderately high spectral resolution, rather than just a number of line-strengths at low resolution, the stellar population analysis is straightforward: the models are simply adjusted to match the observed spectra, with no need of applying tedious and uncertain corrections as in the past. In fact this approach circumvents most of the problems which were lurking the stellar population studies based on the Lick/IDS system. A major challenge is to propose new indicators with unprecedented power for breaking the fundamental degeneracies affecting the integrated light of the stellar systems, such as the age-metallicity degeneracy. These advances will allow us to fully exploit the current high quality data flow from the new generation of large telescopes.

However, we need to improve the main ingredients of the stellar population synthesis models, i.e. stellar tracks with new input physics and in particular new stellar spectral libraries. A major requirement for these libraries is to expand the stellar parameters coverage and to increase the spectral range and resolution, such as the new library by Sánchez-Blázquez et al. (2004, in preparation). This empirical library of flux-calibrated spectra, which is called MILES (MIL EStrellas), is composed of 1000 stars covering the spectral range 3500 – 7500 Å at resolution 2 Å (FWHM). Fig. 3 shows the unprecedented stellar atmospheric parameters coverage of MILES. Fig. 4 shows the spectrum of the galaxy NGC 4478 and overplotted a newly synthesized SSP spectrum based on this library.

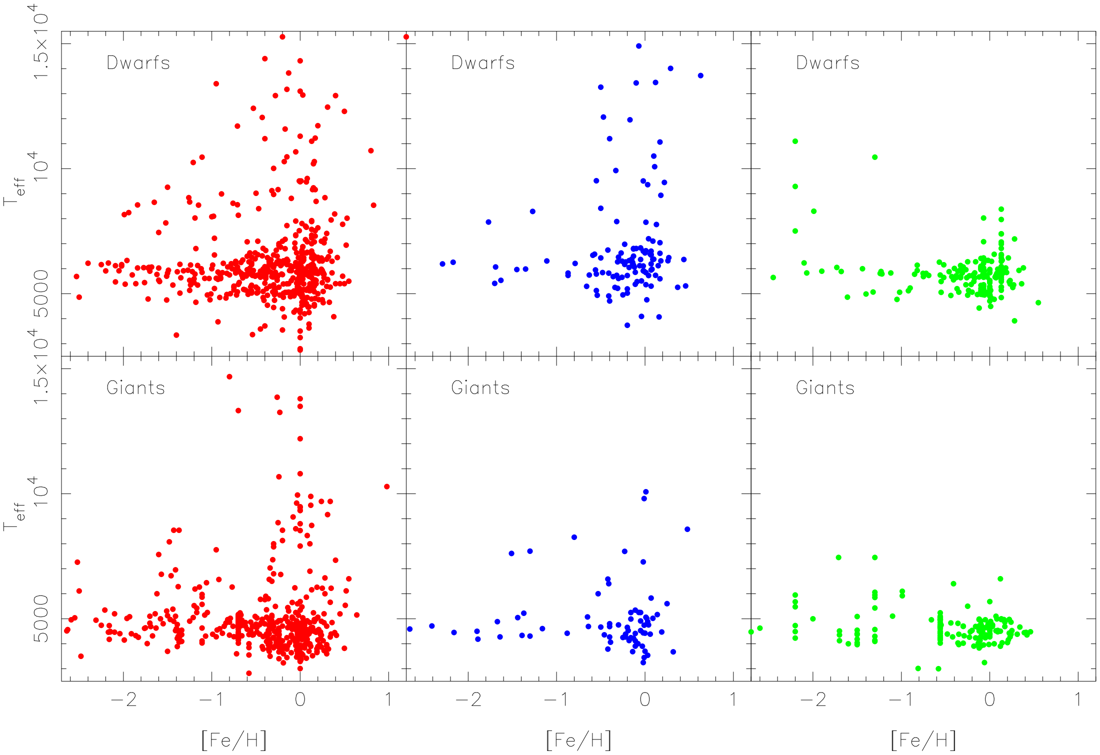

Fig. 3. Comparison of the atmospheric parameters coverage of various empirical stellar spectral libraries. From left to right: plots of T_{eff} versus [Fe/H] for dwarfs (upper panel) and giants (lower panel) for MILES (Sánchez-Blázquez et al. 2004, in prep.), STELIB (Le Borgne et al. 2004) and Lick (Worthey et al. 1994).

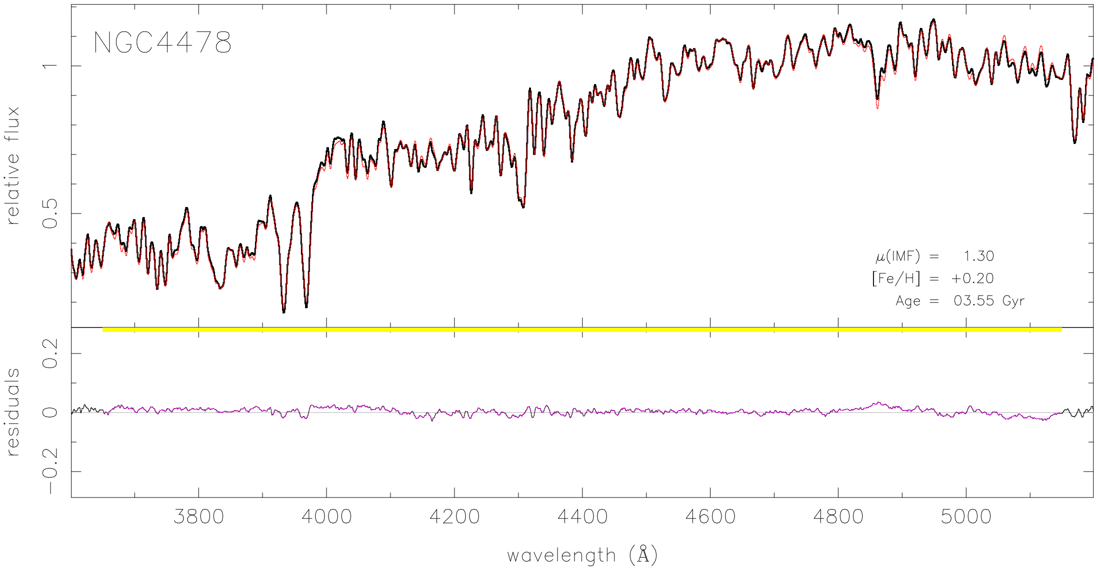

Fig. 4. The spectrum of the central region of NGC 4478 (thick solid line) and overplotted is a synthetic SSP spectrum based on MILES (thin solid line). The model has been smoothed to match measured total velocity dispersion ($\sigma = 150 kms^{-1}$). The residuals are plotted in the lower panel. From Sánchez-Blázquez 2004.

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