Galaxy Evolution and Feedback across Different Environments
Proceedings IAU Symposium No. 359, 2020
T. Storchi-Bergmann, W. Forman, R. Overzier & R. Riffel, eds.
doi:10.1017/S1743921320001647

Recovering the star formation history of galaxies through spectral fitting: Current challenges

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Abstract. With the exception of some nearby galaxies, we cannot resolve stars individually. To recover the galaxies star formation history (SFH), the challenge is to extract information from their integrated spectrum. A widely used tool is the full spectral fitting technique. This consists of combining simple stellar populations (SSPs) of different ages and metallicities to match the integrated spectrum. This technique works well for optical spectra, for metallicities near solar and chemical histories not much different from our Galaxy. For everything else there is room for improvement. With telescopes being able to explore further and further away, and beyond the optical, the improvement of this type of tool is crucial. SSPs use as ingredients isochrones, an initial mass function, and a library of stellar spectra. My focus are the stellar libraries, key ingredient for SSPs. Here I talk about the latest developments of stellar libraries, how they influence the SSPs and how to improve them.

Keywords. atomic data, stars: fundamental parameters, galaxies: stellar content

1. Introduction

Most of the light in galaxies comes from stars. The star formation history (SFH) of galaxies contains information of how they were shaped and evolved. Our knowledge of stars and stellar evolution improved significantly over the last decades, but is based mainly on observing, modelling and interpreting stars of our solar vicinity. However, with the exception of a few nearby galaxies, we cannot resolve stars individually down to the turn-off and below. This means that the information about the star formation history of a given galaxy will be encoded in its integrated spectrum. Extracting physical, chemical and evolutionary information about galaxies from this type of spectrum is one of the major challenges astronomers face today.

Several techniques are available to extract information from integrated spectra, mostly involving the comparison of the observations with stellar population model libraries with a wide range of ages and metallicities (e.g. Cid Fernandes *et al.* 2005; Ocvirk *et al.* 2006; Walcher *et al.* 2006; Koleva *et al.* 2008). This is called full spectral fitting technique. The simplest models used in this technique are the simple stellar population (SSP) models, which are spectra built theoretically using as ingredients isochrones, an initial mass function (IMF), and a library of stellar spectra (e.g. Bruzual 1983; Bressan *et al.* 1994; Worthey 1994; Leitherer *et al.* 1999; Bruzual & Charlot 2003; González-Delgado *et al.* 2005; Maraston 2005; Conroy & Gunn 2010; Vazdekis*et al.* 2010; Meneses-Goytia *et al.* 2015).

Most spectral fitting codes, using different SSPs, produce similar results, but for a minimal S/N, in the optical spectral range and for metallicities close to the solar value. For everything else there is a lot of room for improvement. All the ingredients and codes involved in the creation of SSPs used for the spectral fitting technique had major developments in the last decades, which greatly improved our capacity to interpret integrated spectra. However in all of them there are approximations and imprecisions that might affect the final result. For example, our knowledge of the IMF is based on our interpretation of observations and many assumptions, such as that the IMF is universal and constant in time. Doubts about these assumptions are still in debate today and many studies try to explore different possibilities. (Chiappini *et al.* 2000; Chieffi *et al.* 2002; Bastian *et al.* 2010; Bonatto *et al.* 2012). In the case of the isochrones, there are many aspects of stellar evolution that we still cannot model. Evolutionary effects of chemical variations like α-enhancement (e.g. Salasnich *et al.* 2000; Pietrinferni *et al.* 2009) or individual element variations (e.g. Dotter *et al.* 2007) have been investigated. Problems exist in this field, with different treatments by different groups leading to different evolutionary tracks, even when using the same input parameters (Walche *et al.* 2011; Martins *et al.* 2013).

In the case of stellar libraries, they can be either empirical or theoretical. Empirical libraries are based on observational data, which implies that all features contained in the resulting SSP spectra will be real. The disadvantage, however, is that these libraries are biased towards the star formation and chemical enrichment histories of the solar neighbourhood, the Small and Large Magellanic Clouds or Galactic Globular Clusters (GCs), limiting the coverage and sampling of the Hertzsprung–Russell (HR) diagram. Jain *et al.* 2020 shows that a limited coverage in HR might produce different results when using different empirical libraries.

Theoretical libraries do not have this setback, since it is possible to generate stellar spectra with virtually any temperature or metallicity desired, in any wavelength range, covering the whole parameter space. Of course, this also comes with a limitation, since they are build from models which are always based on physics approximations and simplifications (Bessell *et al.* 1998; Kurucz 2006; Martins & Coelho 2007; Coelho *et al.* 2009; Sansom *et al.* 2013; Kitamura *et al.* 2017). Despite that, theoretical libraries have improved over the years, and it has been shown that their performance is not much worst than that of the empirical libraries (Martins *et al.* 2019). Due to the importance of this ingredient to the quality of SSPs, many groups have been dedicated to create better libraries.

2. Improving theoretical libraries

Martins *et al.* (2019) showed that modern theoretical libraries are capable of reproducing the integrated spectra of globular clusters (GCs) almost as well as empirical libraries. In this work they used a sample of GCs for which there was integrated spectra and CMDs available. For each star in the CMD they associated a spectrum from a given library (they tested two empirical and two synthetic libraries) and with that created an integrated spectrum without the need of an IMF or isochrones. With that they could directly access the quality of each stellar library. Figure 1 shows an example of their results, for the GC NGC 1904. For individual signatures and details of the spectrum, empirical libraries are still better than theoretical ones. But taking the overall shape of the continuum into account, theoretical libraries outperformed the empirical libraries in 13 out of 18 of the cases.

Martins & Coelho (2007) showed that, only by improving the atomic line list used to generate stellar synthetic spectra, it is possible to greatly improve their quality. In general, one half of the discernible lines in observed stellar spectra are missing from the

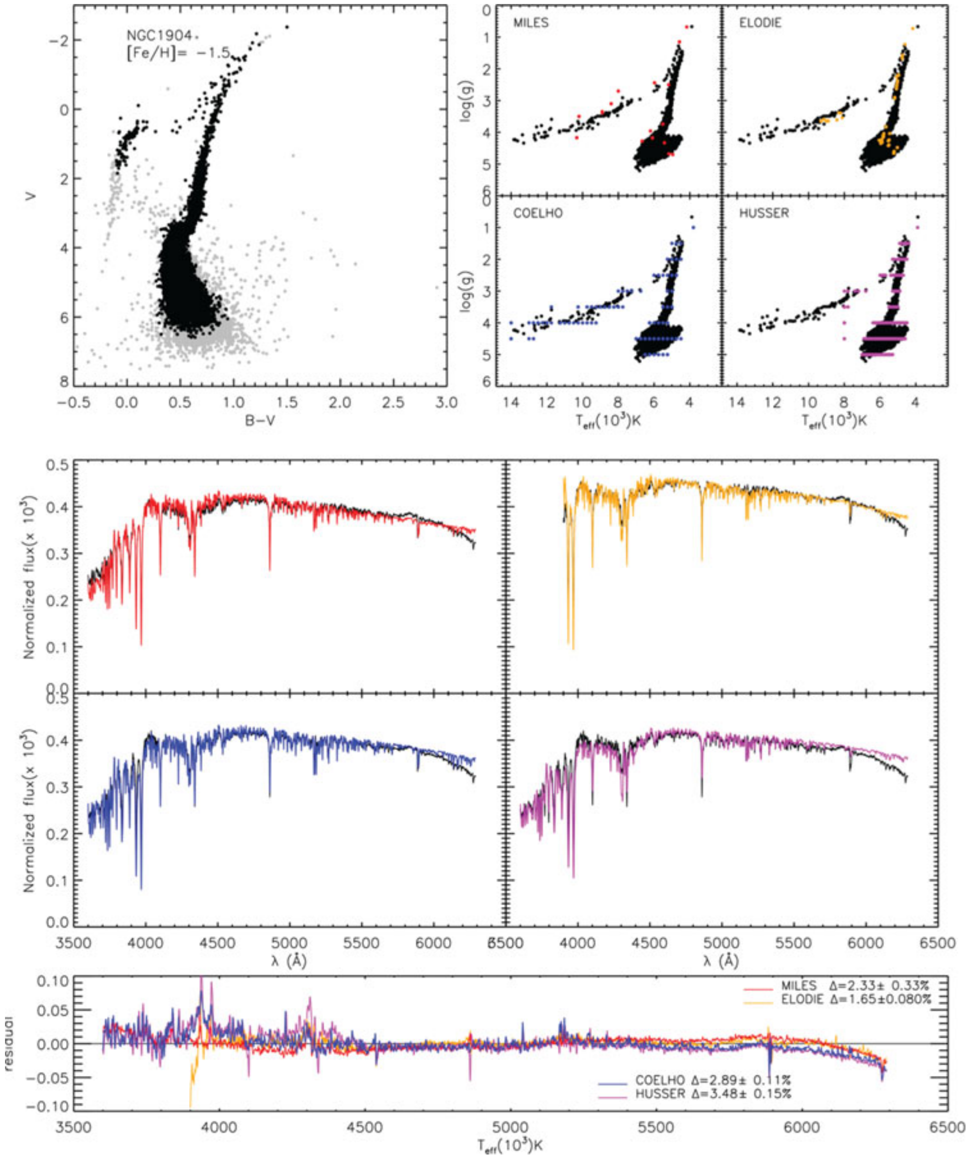

Figure 1. Result of the synthetic spectrum creation for NGC 1904. The top left panel shows the clean CMD used in this work (in black), on top of the original CMD (in gray). The four figures in the top right part of the figure show the $\log g$ vs. $T_{\rm eff}$ diagram, where in black are the stars of the GC and in red, orange, blue and magenta are the selected stars from MILES, ELODIE, COELHO and HUSSER libraries respectively. In the middle panel we show the synthetic spectra created for the GC for each of these libraries. In the bottom panel we show the residual difference (observed - synthetic spectra) for each of the libraries.

line lists with good wavelengths (Kurucz 2011). Efforts are underway to reduce transition probability uncertainties of selected lines (e.g. Fuhr & Wiese 2006; Safronova & Safronova 2010; Wiese, Fuhr & Bridges 2011; Civiš *et al.* 2012) and accurately compute broadening parameters. It has also been shown in the literature (e.g. Barbuy *et al.* 2003; Martins & Coelho 2007) that even empirical calibrations of some specific lines can

https://doi.org/10.1017/S1743921320001647 Published online by Cambridge University Press

produce significant improvement on the synthetic spectra generated. The empirical calibration is done by changing the values of the parameters on the line list, generating models and comparing them with observations of very well known stars (like the Sun or Arcturus, for example). This process is repeated until the results are adequate (Barbuy *et al.* 2003). Franchini *et al.* (2018) is a recent example of this approach. They manually derived oscillator strengths for 2229 lines, an unprecedented effort that greatly improved the quality of their synthetic stellar library, although for a very small wavelength range.

These approaches tend to improve the quality of a selective group lines, mostly those that were considered more suitable to chemical abundance measurements, where relatively weak lines in the linear part of the curve of growth are favoured. On the other hand, the strong lines close to saturation and blended features are the ones which dominate spectral indices in integrated spectra of stellar populations. While these efforts are improving the parameters for thousands of lines, tens of millions of lines are estimated to be needed to compute, say, a complete stellar grid with a good range of atmospheric parameters. Therefore, an innumerous amount of lines remain poorly characterised. For the ultimate goal of computing a large grid of theoretical stellar spectra for further use in automatic classification of stellar spectroscopic surveys and stellar population modelling, this is rather limiting.

Recently, an automatic method has been developed to overcome limitations of the atomic line lists: ALiCCE (Atomic Lines Calibration using the Cross-Entropy Algorithm, Martins *et al.* 2014) is a code developed to automatically calibrate atomic lines using the cross-entropy method. The cross-entropy method is a general Monte Carlo approach to combinatorial and continuous multi-extremal optimisation and importance sampling, which is a general technique for estimating properties of a particular distribution using samples generated randomly from a different statistical distribution rather than the distribution of interest (Rubinstein 1997, 1999). The first application of the code was made by Kitamura *et al.* (2017), to calibrate missing lines in the Solar spectrum. We hope, in the near future, to have improved line lists that will be used to generate more accurate synthetic stellar spectra, improving the quality of theoretical stellar libraries.

3. Conclusion

When using SSP models to interpret the integrated spectra of stellar systems, the user is not always aware of the limitations in these models due its ingredients. It is always important for the stellar population modelling community to try to keep users well informed of the limitations of these models. The accuracy of the techniques using these models have greatly improved over the years, but there is yet a lot of room for improvement. One of the ways stellar population models can be improved is by perfecting one of its main ingredients: the stellar spectral libraries. We developed a code to calibrate the atomic line lists used to generate synthetic stellar spectra, which we believe will be used to create stellar synthetic spectra with unprecedented accuracy. This will certainly expand the applications of SSPs from what we have today.

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