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DESIRABLE EVOLUTIONS OF STELLAR SPECTROSCOPIC SERVICES IN THE LIGHT OF CURRENT STUDIES OF REMOTE STELLAR POPULATIONS.

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Abstract. Recent and future surveys have improved the precision and the accuracy of photometric and spectroscopic observations of remote galaxies. By examining the difficulties encountered in the modelling of these stellar populations, we identify a few key requests to future libraries of stellar spectra and to the related spectroscopic services. Beside providing data access, future services should increasingly focus on the associated on-line and off-line tools required to model and analyse galaxy spectra.

Keywords: stars, stellar populations

1 Introduction

Over the last decade, the tremendous progress of the quality of observational data has in some areas left model developments behind. The uncertainties in galaxy observations, for instance, have become small compared to the errors in population synthesis models. Although models can be fitted to high quality spectra of galaxies with residuals as low as two or three percent, these deviations are often significantly larger than the observational errors, implying systematic errors in the estimated astrophysical properties. It is by digging into these residuals that our understanding of the star formation and metal enrichment histories of stellar populations will progress. Some of the recurrent difficulties can be traced back to the adopted stellar spectral libraries, or to the algorithms used to associate a spectrum with any point along a stellar evolution track.

Stellar spectral libraries, a core ingredient of population synthesis tools, come in a variety of flavours. Some are theoretical, others empirical, and semi-empirical combinations are also common. The properties most important for the synthesis of stellar populations are a broad spectral coverage, an extensive coverage of the natural range of stellar physical parameters, and a good accuracy of the stellar energy distributions. A high spectral resolution is desirable for studies of nearby populations, that can be resolved into individual stars, but an intermediate resolution ($\lambda/\delta\lambda \sim 10000$) is satisfactory to study even the lowest mass unresolved galaxies.

The list of existing stellar spectral libraries is too long to be given here. The access to these public data is not anymore a bottleneck, and we are now facing other difficulties: (i) the description of these data is sometimes limited, (ii) the sampling of physical parameter space could be improved, and (iii) the tools, be they associated to the on-line archives or imbedded in public software packages for an off-line usage, lack the detailed descriptions that are needed to unveil the causes of the differences between stellar population model predictions.

In the following, we explicit a few of the practical difficulties met today when comparing the predictions of population synthesis codes with observations, and we identify paths along which work directly related to spectroscopic services could help achieve significant improvements. These future services shall not only focus on the data access, but also on all the on-line and off-line tools needed for the usage and interpretation of spectra.

2 Spectroscopy

Two recent empirical spectroscopic libraries successfully used in the analysis of optical spectra of stellar populations are Miles (Sánchez-Blázquez et al. 2006) and Elodie (Prugniel & Soubiran 2001). Both cover a wide

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range of stellar parameters, thus allowing studies of populations of all ages and metallicities. The libraries carry the chemical signatures of the Milky Way, in particular the anti-correlation between [Fe/H] and [α/Fe], but methods have been devised to correct for this bias based on the differential effects of α-enhancements in theoretical spectra (Prugniel & Koleva 2012; Vazdekis et al. 2015). The spectra are available through web sites that also provide estimated parameters, and articles describe their intrinsic properties (signal-to-noise ratio, line spread function). Last but not least, successful interpolators are available for these libraries (Prugniel & Soubiran 2001; Vazdekis et al. 2010; Sharma et al. 2016).

Interpolators, once trained on the available spectra, predict spectra for any position in the space of stellar parameters (effective temperature, gravity, metallicity, etc.). The polynomial form of the imbedded predictive model ensures numerical efficiency in the generation of population synthesis models, and is also a key to efficient fitting of new spectra (Koleva et al. 2009; Rix et al. 2016). With the Miles or Elodie libraries and the corresponding interpolators, fit residuals to star and stellar population spectra are regularly seen to stay below 2% (Prugniel et al. 2007). Internal errors on derived population parameters are small, and in particular much smaller than the systematic differences between the results obtained using different population synthesis codes (Koleva et al. 2008).

So where is improvement needed? An obvious path is the extension to non-optical wavelength. A few models have included empirical extensions to the ultraviolet or the near-infrared, but as yet for a restricted range of metallicities (e.g. Mouhcine & Lançon 2002; Maraston 2005; Lançon et al. 2007a; Vazdekis et al. 2016; Röck et al. 2016). The Xshooter Spectral Library XSL, with more than 600 spectra at $\lambda/\delta\lambda \sim 10000$ between 310 and 2400 nm, is designed to allow more variety (Chen et al. 2014). The ongoing studies of these spectra highlight that it is difficult to find theoretical spectra that will match the data satisfactorily at all wavelengths. The fundamental parameters of the stars usually determined from a restricted spectral range are not usually sufficient to obtain a good model fit everywhere else, and this suggests there may be biases in the parameter estimates as a consequence of inadequate assumptions for other ingredients of the models (e.g. turbulent velocities). Also, it is clear that despite steady advances much progress is still needed in lists of atomic and molecular data. The fits of observed spectra (of stars or galaxies) with purely theoretical spectra still have much larger residuals than fits with interpolated empirical spectra.

Two or three technical issues could be solved in the nearby future.

One is interpolation. The interpolators that work satisfactorily for empirical libraries do not seem to perform as well when applied to the regular grids of theoretical models. The analysis of new spectra with the latter tend to produce distributions in parameter space (such as the HR diagram) that show systematic local deviations from the loci expected from stellar theory. One of the reasons may be that parameter space is undersampled in certain parts, while unnecessary models exist for parameters that do not occur in natural stars. This aspect has been discussed recently by Ting et al. (2016), and more work is needed to identify an optimal sampling strategy for future calculations of synthetic spectra in the case of broad wavelength ranges, extended temperature and gravity ranges, and spectra that are not normalised to a continuum of one. The nature of the interpolation should also be optimised: what prior normalisation of complete UV-to-infrared spectra is adequate? can transformations of the flux variable (for instance the use of its logarithm) be useful in certain regimes? Finally, the synthetic spectra themselves must still be questioned. When large grids of such spectra are computed, local convergence problems may go unnoticed, leading to small amplitude artificial discontinuities in the variations of fluxes with certain physical parameters.

Another path of progress is the choice of abundance patterns in synthetic libraries, and the description thereof. The surface abundances of stars are known to vary with time, for instance via diffusion and convection (dredge-up). In contrast, the vast majority of grids of synthetic stellar spectra provide grids for the whole HR diagram at constant abundance ratios. Considering the importance of C, N, O in shaping the spectra of luminous red stars (e.g. Lançon et al. 2007b; Aringer et al. 2016), variants with evolutionary-driven abundance patterns should be computed more systematically. Light element abundances variations add to those of α-elements, for which more information is fortunately available in the literature. Finally, we note that the role of helium may still be underestimated when computing synthetic spectra, although its importance in shaping stellar evolution tracks is clear. A brief study was presented by Girardi et al. (2007), using grids in which Y was varied at a given Z. The reference grid in this study had the same Y for all Z (i.e. $\Delta Y/\Delta Z = 0$). The recent grid of Husser et al. (2013) offers spectra for a broad range of [Fe/H] and [α/Fe], but with constant [He/H] (i.e. $\Delta Y/\Delta Z < 0$). In contrast, stellar evolution models usually assume positive (and sometimes quite large) values of $\Delta Y/\Delta Z$. This makes it difficult to map points along evolutionary tracks to spectra in the theoretical grids. Fortunately, the awareness of the need for consistency with known evolutionary trends is

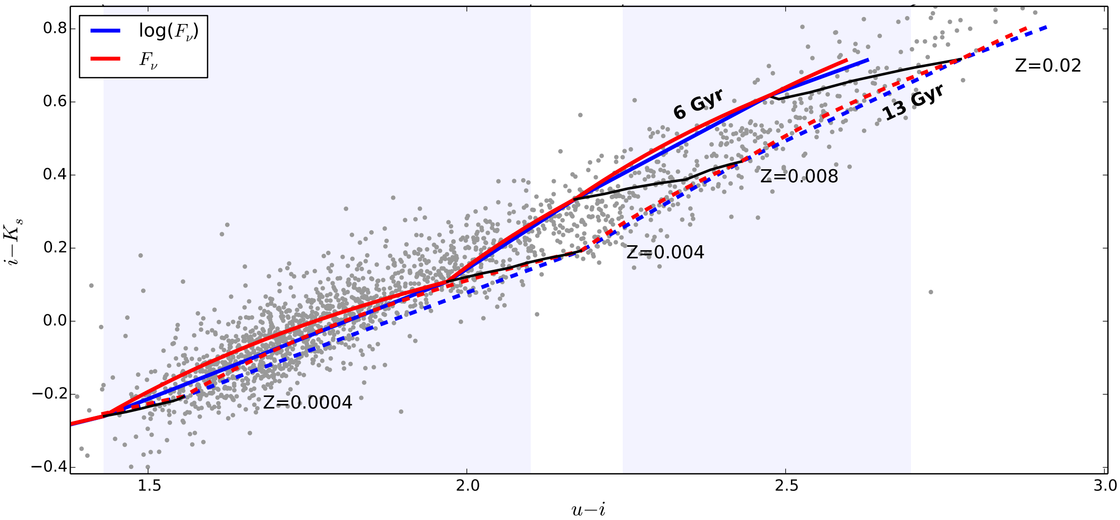

Fig. 1. Colors of globular clusters in the core of the Virgo cluster (grey dots, from Powalka et al. 2016), and population synthesis predictons at ages of 6 Gyr (solid) and 13 Gyr (dashed). The intrinsic metallicity sampling of the models is indicated. It is scarce at low Z. Red and blue lines are obtained, respectively, when interpolating fluxes or their logarithms. At low metallicity, choosing one or the other leads to large age differences.

rising (e.g. Coelho 2014). Future spectroscopic services could usefully include tools to standardise the chemical information provided by the authors, for instance to convert [Fe/H] and a reference for the solar composition into a full list of elemental abundances.

3 Photometry

Although photometric studies of stellar populations are plagued by stronger degeneracies than spectroscopic studies, they will remain necessary, being the only way to assess faint remote galaxies or to obtain an exhaustive coverage of a large area of the sky. To predict the colours of galaxies in the local universe, tables of stellar bolometric corrections are sufficient, but broad baseline spectral libraries remain necessary for the computation of $k-$corrections (i.e. photometry at non-zero redshift).

Colors of galaxies or star clusters are already available with a precision better than a percent, and an accuracy thought to be better than 2 %. Differences between the predictions of various families of population synthesis models are much larger. Powalka et al. (2016) demonstrated this in a comparison between various model sequences and $\sim$ 1700 globular clusters (GC) of the core of the Virgo galaxy cluster, showing that none our of 11 model families was able to match the locus of the GC in u, g, r, i, z, K_s. Analogous difficulties were found for younger star clusters, local galaxies or redshifted galaxies, e.g. by Wofford et al. (2016), Hansson et al. (2012), Taylor et al. (2011).

Not all the difficulties come from the stellar spectral libraries or the way these are implemented, but some definitely do. A very careful flux calibration of empirical libraries is necessary to match optical colours of stellar populations (Ricciardelli et al. 2012; Maraston & Strömbäck 2011). The XSL project is still working on extending this effort to the near-infrared. On the theoretical side, Coelho (2014) emphasise that stellar radiative transfer calculations designed for the prediction of high resolution spectra or of broad band fluxes are not always consistent: lists of lines with uncertain theoretical properties (strength and wavelength) are sometimes left out from high resolution calculations to avoid confusion, while they are included at low resolutions. Differences between the resulting broad band flux levels exceed 20 % at optical and near-UV wavelengths in some temperature regimes.

Direct ways of testing the photometric accuracy of synthetic stellar libraries are available. The colours of dwarfs can be tested against the stellar locus of deep multi-band surveys. For instance, Powalka et al. (2016) showed that the u, g, r, i, z, K_s colours of Phoenix-based models (Husser et al. 2013) are in good agreement with those measured in the NGVS survey (Ferrarese et al. 2012), provided the variations of mean [Fe/H] and [α/Fe] along the locus are properly taken into account (however this does not guarantee all spectral features are well-modelled in detail). HST and ground-based observations of numerous star clusters make it possible to extend such studies to giants.

Finally, Figure 1 illustrates how interpolation choices may affect photometric age estimates, in regimes where the sampling step in the stellar libraries are large. Progress on interpolation strategies combined a better sampling of stellar parameter space, will help photometric studies as much as spectroscopic ones.

4 Conclusions

Coming extensions of libraries of stellar spectra (wavelength range, number of spectra) will improve stellar population models, but we have identified a number of studies that will need to be conducted in parallel in order to achieve the accuracy required for the analysis of modern galaxy data. Interpolation tools will have to be developed even further, and photometric accuracy ensured. Emerging strategies for the sampling of parameter space in the calculation of new grids of theoretical spectra will need to be extended into the regime of multi-wavelength spectrophotometric data useful for population synthesis, taking into account the evolution of stellar surface chemistries. Spectroscopic services around the on-line data can play a decisive role by making tools and descriptions available that will facilitate the intercomparison between data sets and between library implementation methods.

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