Grids of Synthetic Stellar Spectra

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Grids of Synthetic Stellar Spectra

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Abstract

Grids of stellar spectra are extensively used in astrophysics in a range of applications, from derivation of atmospheric parameters in observed stellar spectra, to archaeological studies in integrated light of galaxies. Theoretical stellar libraries have been increasingly used in recent years to overcome limitations of empirical libraries by, e.g., exploring atmospheric parameter spaces not well represented in the latter. Nevertheless, there are still caveats and they can only partially model observations with accuracy. Here we discuss the current need for synthetic libraries, in particular for applications in stellar population studies. Next we briefly present a non-extensive sample of libraries available in literature, and we then highlight how better atomic and molecular opacities are much needed to overcome the deficiencies of current synthetic libraries.

Keywords: spectroscopy; stellar spectral libraries; atomic spectra

1 The need for synthetic grids

Libraries of stellar spectra are fundamental in many different fields in astrophysics. For example, they serve as reference for the classification and automatic analysis of large stellar spectroscopic surveys, while are also fundamental ingredients in models of stellar populations used to study the evolution of galaxies.

A good stellar library should ideally provide complete coverage of the HR diagram, accurate atmospheric parameters (effective temperature T_{eff} , surface gravities $\log g$, metallicities

Z and abundances $[\text{Fe}/\text{H}]$, $[\text{Mg}/\text{Fe}]$, etc.), and good wavelength coverage and/or good spectral resolution, depending on the aimed application. Either empirical or theoretical libraries can be used, for example, in stellar population (SP) modeling and both types have improved dramatically in recent years [see e.g. 1].

Empirical libraries are homogeneous compilations of observed stellar spectra, and are the ones mostly used for stellar population applications [e.g 2, 3]. Being based on real stars, the major advantage of an empirical library is that the spectral properties are ultimately reliable, lim-

ited only by the quality of the observations. High quality observations are limited to the closest stars, and thus the coverage of the HR diagram and abundances are biased towards the stellar population of the sample. The main caveat of empirical libraries is their limited coverage of the HR diagram, and stellar population models based solely on them are not able to reproduce consistently the medium to high resolution spectral features of systems which have undergone a star formation history different than the stars in the library [e.g. 4]. Theoretical libraries must be used to overcome this limitation, either solely or in combination with empirical libraries [e.g. 5, 6, 7].

A synthetic (or theoretical) spectral library is based on model atmospheres predictions and atomic and molecular line lists [8, 9, 10]. These model atmospheres may include simplifications for complex physical process (such as convection) or computational limitations (for example, geometry and/or boundary conditions) and often they depend on incomplete or imprecise atomic and molecular opacities [11]. Theoretical libraries can cover the parameter space in T_{eff} , $\log g$, and abundances to a large extent, making them very powerful to overcome the limitations of empirical libraries. Moreover, a synthetic star has very well defined atmospheric parameters, infinite S/N, and covers larger wavelength ranges at higher resolutions than observed spectra. Nevertheless, theoretical libraries are based on our knowledge of the physics of stellar atmospheres and databases of atomic and molecular transitions, and as such they carry the uncertainties of their underlying models and input data.

2 Libraries available

Despite caveats, further explored in the next section, synthetic libraries are the best available tool to model and study the spectral properties of a wide range of stellar populations. A large "industry" for computing libraries exists, and a sample of libraries published in the last decade is compiled in Table 1. A more extensive compilation of libraries, both synthetic and empirical, can be found at <http://pendientedemigracion.ucm.es/info/Astrof/invest/actividad/spectra.html>.

Our host and chair of the conference, Beatriz Barbuy, has started a community in São Paulo which built a tradition in modelling and making use of synthetic grids. The contributions from São Paulo astronomical community date back to late 80s [12, 13], and cover:

- improvements in line lists [14, 15, 16];
- synthetic grids, including modelling of spectral indices [17, 18, 19, 20, 21, 22, 23], and;
- the modelling of stellar populations with synthetic grids [24, 25, 26, 27].

3 Improvements needed

Several work in literature has illustrated the ability of synthetic libraries to reproduce (or not) observations [e.g. 40, 41, 23]. In [23], the author performs a careful comparison of a synthetic grid with the empirical library MILES [2]. The results show that above $T_{\text{eff}} \geq 6000$ K, models can reproduce observed fluxes within a typical deviation of 2%. Deviation rises steadily towards cooler temperatures, reaching 10% at

Table 1: A sample of synthetic libraries published over the last decade

Reference	Coverage in atmospheric parameters	Wavelength coverage
[21]	Spectral types F, G, K, early M	300nm – 1.8 μ m
[22]	3000 K $\leq T_{\text{eff}} \leq$ 55000 K; $-0.5 \leq \log g \leq$ 5.5; $-1.0 \leq [\text{M}/\text{H}] \leq +0.3$	300 – 700nm
[28]	3500 $\leq T_{\text{eff}} \leq$ 47 500 K; $0.0 \leq \log g \leq$ 5.0; $2.5 \leq [\text{M}/\text{H}] \leq$ 0.5; $[\alpha/\text{Fe}] = 0.0, +0.4$	250 – 1050 nm
[29]	3000 $\leq T_{\text{eff}} \leq$ 50000 K; $0.0 \leq \log g \leq$ 5.0; $-2.0 \leq [\text{M}/\text{H}] \leq +0.5$	85 – 470nm
[30, 31] and references therein	Spectral types O and B, also models with accretion disks (Cataclismic Variables, X-Ray binaries)	90 – 750nm (HIGH-RES); 4.5nm – 300 μ m (SED)
[32]	Spectral types from O to M, A-peculiar, Emission lines, White Dwarfs	300 – 1100nm
[33]	$\log(L) \geq 2.75 L_{\text{sun}}$ and $T_{\text{eff}} \geq 20,000\text{K}$	90 – 300nm
[34]	Spectral types from O to M	300 to 1200nm (HIGH-RES); UV to NIR (SED)
[35]	3500 K $\leq T_{\text{eff}} \leq$ 8000 K; $0.0 \leq \log g \leq$ 5.0; $-4.0 \leq [\text{M}/\text{H}] \leq$ 0.0; $-0.8 \leq [\alpha/\text{Fe}] \leq +1.2$	630 – 910nm
[36]	2300 K $\leq T_{\text{eff}} \leq$ 12000 K; $0.0 \leq \log g \leq$ +6.0; $-4.0 \leq [\text{Fe}/\text{H}] \leq +1.0$; $-0.2 \leq [\alpha/\text{Fe}] \leq +1.2$	50nm – 5.5 μ m
[23]	3000 K $\leq T_{\text{eff}} \leq$ 25 000 K; $-0.5 \leq \log g \leq$ +5.5; $-1.0 \leq [\text{Fe}/\text{H}] \leq +0.2$; $[\alpha/\text{Fe}] = 0.0$ and 0.4	250 – 900nm (HIGH-RES); 130nm – 100 μ m (SED)
[37, 38, 39]	Models for Wolf-Rayet stars, several abundance patterns	20 – 8000nm

$T_{\text{eff}} = 4000\text{ K}$. The work also identifies wavelength regions where models deviate from observations systematically [Fig. 10 in 23].

The origin of the deficiencies in the theoretical predictions may be two-fold: the underlying physics theory and/or the input physics data (atomic and molecular opacities) of the models. In terms of physics theory, state-of-the-

art hydrodynamical models are an important recent advancement [e.g. 42, 43], but these models are considerably time-consuming and until now no extensive grids of 3D models exist. In the hot stars regime, models taking into account N-LTE effects are mature and grids of N-LTE line-blanketed model atmospheres and fluxes of O- and B-type stars are available in literature [e.g.

44, 45, 22]. Progress is being made.

In terms of physics basic data, databases of atomic and molecular transitions provide fewer lines with highly accurate oscillator strengths and broadening parameters than we would like, besides being often incomplete [46]. Constant updates and improvements are necessary from laboratory data, critical compilations, empirical adjustments and improved quantum mechanics computations [e.g. 47, 48, 49].

Many groups are working through the years to improve the quality of atomic data. Advancements have been made in:

- reducing the uncertainty of the transition probabilities [e.g. 50, 51, 52, 53, 54, 55, 48, 56, 57];
- reducing uncertainties of the broadening parameters [e.g. 58, 59, 60, 61, 62, 51, 63, 64], and;
- many limitations of these atomic line lists are being overcome by different methods and authors, mostly aiming at chemical analyses of stellar photospheres using high resolution spectra [e.g. 65, 66, 67, 68, 69, 70, 71]

Recently, an automatic method has been developed to overcome limitations of the atomic line lists: ALiCCE [Atomic Lines Calibration using the Cross-Entropy Algorithm, 16] 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 optimization 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 [72, 73, 74].

The first application of the code was made by Kitamura et al. (submitted to MNRAS), 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.

4 Conclusions

With the high quality and high spectral resolution observations we have available today, the applications of empirical stellar libraries are mostly restricted to stellar populations which have star formation histories similar to our solar neighborhood. Synthetic stellar libraries might be the only solution to study the majority of extragalactic stellar systems. As the observations of such systems improve, it is our opinion that the next generations of spectral stellar libraries will tend more and more towards theoretical libraries, with empirical libraries being used for (the much crucial) testing and calibration of the theoretical spectra.

The quality of synthetic spectra have steadily grown over the last decades, but there is still plenty of room for improvement. One of the aspects which still requires improvement are the line lists used to generate the synthetic spectra. Quoting [75], “*The most sophisticated 3-D hydrodynamics calculations for stars are still wrong if the opacities are wrong*”. In this context, we believe that new automatic calibration methods such as the code ALiCCE might bring great advances.

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