Measuring Stellar Atmospheric Parameters with ARES+MOOG

S. G. Sousa and D. T. Andreasen

Abstract The technical aspects in the use of an Equivalent Width (EW) method are described for the derivation of spectroscopic stellar parameters with ARES+MOOG. While the science description behind this method can be found in many references, here the goal is to provide a user manual approach for the codes and scripts presented in for the tutorial. All the required data is available online.

1 Introduction

Several methods are used for the derivation of stellar spectroscopic parameters. These can be divided into two main groups. One based on spectral synthesis for which synthetic spectra are created and compared with the observed spectrum to find the best fit. The second group adopts a line by line analysis strategy, measuring the strength of observed spectral lines and then estimating abundances and applying Physics criteria such as the ionization and excitation balance to find the best spectroscopic stellar parameters for the observations. The description of the physics behind these methods can be found in many books.

A brief work-flow for an EW method can be described as follows: For a high quality observed stellar spectrum, starting by measuring the strength of several spectral lines (e.g. EWs with ARES). These measurements are then converted into individual line abundances which are computed (e.g. with MOOG) using stellar atmospheric models, normally assuming Local Thermodynamical Equilibrium (LTE)
approximation. The model parameters are then adjusted until the individual line abundances show evidence of the excitation and ionization balance. This step can be automatized if a proper minimization method is adopted.

The rest of the document will focus on the technical aspects of the codes provided for this tutorial and how a student can use them to actually derive spectroscopic stellar parameters. A more specific description of the ARES+MOOG method can be found in [5]. The next sections will be based on the codes and test data available online.

2 Requirements

This tutorial was implemented to be executed on a Linux machine. Note that even without an access to a Linux machine, today it is very easy to emulate one by using virtual machines (e.g. VirtualBox). All the instructions provided both in this document and in the repository are compatible for Debian/Ubuntu systems, but can be easily adapted for other Linux flavors.

2.1 Main codes for the tutorial

ARES

ARES is a C code that allows a fast and automatic measurement of EWs of spectral absorption lines. The ARES code is a submodule in the school\_codes repository and therefore easily updated with the root ARES repository\(^2\) which contains more information. For a more detailed description of the code please see the ARES papers \(^2\)\(^4\). Note that the latest version of ARES is already able to deal with in-situ radial velocity correction and automatic parameterization for the continuum level which makes the spectral analysis easier and consistent. In order to compile ARES it is required some external libraries (e.g. CFITSIO, GSL, etc.) which can be easily installed in Linux machines. The compilation of the code is then handled by the Makefile provided in the repository.

MOOG

MOOG is a code that performs a variety of LTE spectral analysis. The original code can also be found in its homepage\(^3\). The code available in the school\_codes repository is an adapted version of MOOG2014 modified to neglect its (non-free)

\(^2\) https://github.com/sousasag/ARES
\(^3\) http://www.as.utexas.edu/~chris/moog.html
plot library dependency. In this tutorial it is only used the silent version of the code to make abundance computations for our EW method. The compilation of the code is also handled by the Makefile.

2.2 Spectral test data

Observed Spectrum

The spectra for the analysis should be of good quality, in terms of resolution (R > 30000) and signal-to-noise ratio (S/N > 100). Three HARPS spectra are provided for the tutorial. These spectra have R ~ 110000, and S/N > 300. These spectra is provided in the folder spectra of the repository. These are standard FITS 1D spectra. In order to be compatible with ARES they need to have the standard keywords CDELT1 and CRVAL1 and the units of the wavelengths should be Angstrom. Alternatively ARES can also read ASCII spectra where the format must be two columns, the first with the wavelengths and the second with the flux. In this tutorial only the standard 1D fits files are used.

Linelist

The strength of specific absorption spectral lines should be measured in this analysis. As in most EW methods, iron lines are mostly used because they strongly populate the solar-type spectrum and because iron can be used as a proxy for the stellar metallicity. The linelist provided online (iron lines_parameters.dat) compiles 263 Fe I and 36 Fe II lines. These lines were carefully selected [3] and its atomic data were revised using a solar spectrum as a reference making it possible to use of a differential analysis [5]. This linelist is used both for ARES and MOOG. For ARES the important information is only the wavelength of the lines. The format in this case is to keep the first column as wavelength in Angstrom. For the individual abundance computation MOOG needs the atomic data, the Excitation Potential (E.P.), and oscillator strengths (log gf), the 2nd and 3rd columns respectively. The format of this file should be kept fixed so the scripts work without a problem.

2.3 Script Codes

Input linelist for MOOG

The EW measurements and the atomic data for the linelist require a special format to be used by MOOG. To facilitate this task it is provided a python script
Creating a stellar atmospheric model

For the computation of the individual line abundance it is required the use an atmospheric stellar model. MARCS models are used in this tutorial. For this task it is provided a script that interpolates a grid of MARCS models for specific stellar parameters. The folder \texttt{interpol\_models\_marcs} in the repository includes a script for this task. In order to make it work, it is first required to follow the instructions to download and extract the grid of MARCS models. The use of the script to get a specific atmospheric stellar model is straightforward and it will be described later in this document.

Excitation and Ionization Correlation

To understand how the individual line abundances depend on the stellar atmospheric parameters and how to find the best stellar parameters, it is provided a plotting script that allows the visualization of the correlations/indicators needed to constrain the parameters. These include the abundance vs. E.P., abundance vs. Reduced EW., the information on $|\langle FeI \rangle - \langle FeII \rangle|$ and the average [Fe/H] compared with the model [M/H]. For more details about these indicators see section 5 and 6. The python script (\texttt{running\_dir/read\_moog\_plot.py}) allows to plot these correlations as well as display the information of these indicators as it is presented later in Fig.1 and 2.

3 Step by Step Tutorial

The criteria to derive good spectroscopic parameters with this method rely on the model that enforces the excitation and ionization balance for the line abundances. Therefore the final step of this iterative method is when it is found the same abundance for all the lines which will translate in zero slopes for abundance vs. E.P., abundance vs. Reduced EW. and $\langle FeI \rangle = \langle FeII \rangle$. How to reach this? The steps to derive stellar parameters, where the spectrum TestA.fits is used for this example, are described as follow:

1. **Location**: To start the process lets first define a reference folder. Let the folder \texttt{running\_dir} be our reference in order to run the codes and scripts in this tutorial. To confirm this, when displaying the spectra available in the repository the result should be:

\begin{verbatim}
marcs.astro.uu.se
\end{verbatim}
2. Measuring EWs: In this folder it is already present the required ARES input file (mine.opt) containing the recommended parameters for high quality spectra. Details for these parameters may be found in [2,5]. Running ARES will display plenty of information in the terminal. In the end the output file (TestA.ares) will be created as well as a log file (logARES.txt) containing all the relevant information. To run ARES for the TestA.fits spectrum:

```bash
running_dir$ ../ARES/./ARES
```

3. MOOG input linelist: To create the line list with the EWs in the correct format it should be provided the ares output file (TestA.ares) as well as the linelist with the reference atomic data (ironlines_parameters.dat). This can be done with:

```bash
running_dir$ .././make_moog_lines.py TestA.ares ../ironlines_parameters.dat
```

Saved in: lines.TestA.ares

4. Loop start: The beginning of the iteration loop is here where it is created a specific MARCS model. Starting the loop with parameters that represent an average dwarf solar type star (Teff: 5500 K, logg: 4.40 dex, [M/H] = 0 dex, 
v\text{tur} = 1.0 km/s), to generate this model (creating the file out_marcs.atm):

```bash
running_dir$ ../interpol_models_marcs/./make_model_marcs.bash 5500 4.4 0.0 1.0
```

5. MOOG: The next iterative step is to compute the individual line abundances assuming the stellar atmospheric model. For this step MOOG will use an already defined input file (batch.par) and will then create an output file with the computed line abundances (output.moog). To run MOOG in its silent mode:

```bash
running_dir$ ../MOOG2014/./MOOGSILENT
```

6. Control check: This is the crucial step where it is validated the stellar parameters for the model. Again, good parameters are found when the same abundance is derived for all the lines. The slopes should therefore be negligible (all indicators having values < 0.005 is a good criteria). If significant correlations are found in these indicators, these can be used to adjust the parameters back in step 4. To check the status of these indicators the plotting python script can be used:

```bash
running_dir$ python read_moog_plot.py output.moog
```

| Model Parameters: Teff logg vtur [M/H] |
|----------------------------------------|
| 5500 4.4 1.00 0.00                     |

```
Model Parameters:
Teff = 5500 K
logg = 4.40 dex
[M/H] = 0.00 dex
v\text{tur} = 1.0 km/s
```

```bash
running_dir$ python read_moog_plot.py output.moog
```

```
Model Parameters:
Teff = 5500 K
logg = 4.40 dex
[M/H] = 0.00 dex
v\text{tur} = 1.0 km/s
```

Note that the mine.opt file should be adapted for the other test spectrum.
Figure 1 shows the plots that appear in the last step. The indicators values for this first iteration are far from zero. Therefore it is require to go back to step 4 and try different parameters. The strategy to minimize this problem and change the parameters in the correct direction is discussed in the next section.

### 4 The strategy to find the best parameters

In this section it is briefly described the technical strategy to find the best model. A complete description of this strategy is found in [5]. From figure 1 the four indicators values provide the necessary hints to reach a better model for the next iteration.

- **Slope E.P.**: This indicator is the one that strongly depends on the temperature of the model. Negative values of this slope means that the correct temperature should be lower. To fix positive values the temperature should increase in the next iteration. This indicator controls the excitation balance. Given the very high number of iron lines, the temperature is one of the best constrained parameters with this method.

- **Slope R.W.**: This indicator is connected with the microturbulance parameter which basically controls the abundance determination for the stronger lines where saturation becomes specially significant in the wings of the absorption lines [1]. For negative slopes the microturbulance should be reduced, while positive values it means the microturbulance is overestimated.
• **Fe I** or **Fe II**: Since FeII lines are more sensitive to surface gravity than FeI lines, this indicator can be used to control the \( \log g \) of the model. For negative values then \( \log g \) should decrease for the next iteration, while for positive values \( \log g \) should be higher.

• **[Fe/H] = [M/H]**: More than an indicator, this is actually a logical physical constraint for the model. Meaning that the input metallicity should output a compatible global iron abundance. Here it is assumed that the iron abundance is a proxy for the stellar metallicity. Therefore if the iron abundance is larger than the model metallicity (positive indicator) then it should be increased for the next iteration. If the indicator is negative this means that the metallicity of the model is overestimated.

These indicators can be used to find a better model for the spectrum TestA.fits. Figure 2 shows one good result for a model with \( T_{\text{eff}} \): 5838 K, \( \log g \): 4.34 dex, \( [M/H] = 0.25 \), \( v_{\text{rot}} = 1.08 \) km/s. With this model all the indicators are close to zero (all < 0.005). These results can still improve, given the clear presence of outliers in the figure. In this case most of these outliers are overestimating the iron abundance (compared with the average). The cause for this may be related with less reliable, and overestimated, EW measurements for those specific spectral lines and therefore removing these outliers will improve the result.

For this tutorial, it is provided in table 4 the identification of the stars for each test spectrum provided. The table also summarizes the stellar parameters which were derived by using the same method with remotion of outliers. For the spectrum TestA.fits, which correspond to HD128620 (also known as \( \alpha \) Cen A) the results are quite close to the ones presented in Fig. 2. Note that temperature is within 10 K, and the metallicity should be slightly lower (by only 0.02 dex) as expected given
that the outliers overestimate the iron abundance. Although here it is not discussed any error analysis for this method, it is clear from the results that the precision of the method is quite high, just by considering the very low spread of the parameters derived without the lines with problematic EW measurements.

| File   | Star     | Teff (K) | log g (dex) | [Fe/H] (dex) | $V_{\text{tur}}$ (km/s) |
|--------|----------|----------|-------------|-------------|--------------------------|
| TestA.fits | HD128620  | 5832     | 4.33        | 0.23        | 1.11                     |
| TestB.fits | HD128621  | 5234     | 4.40        | 0.16        | 0.90                     |
| TestC.fits | HD179949  | 6287     | 4.54        | 0.21        | 1.36                     |

5 Summary

The technical aspects were presented for running the tutorial to derive spectroscopic stellar parameters with the ARES+MOOG EW method. The strategy for finding a good model based on the indicators provided for each iteration is briefly described. This document is a complement for the material provided online. For a more complete understanding of the ARES+MOOG method it is strongly advised the reading of previous works\cite{2,4,5}.

Acknowledgements

"S.G.S and D.T.A. acknowledges the support by Fundao para a Cilncia e Tecnologia (FCT) through national funds and a research grant (project ref. UID/FIS/04434/2013, PTDC/FIS-AST/7073/2014, and grant ref: CAUP-09/2014-BD). S.G.S. also acknowledge the support from FCT through Investigador FCT contract of reference IF/00028/2014 and POPH/FSE (EC) by FEDER funding through the program Programa Operacional de Factores de Competitividad COMPETE.

References

1. Gray, D. F.: The Observation and Analysis of Stellar Photospheres, Cambridge, UK: Cambridge University Press, 2008
2. Sousa, S. G. et al.: Astronomy & Astrophysics, Volume 469, Issue 2, July II 2007, pp.783-791
3. Sousa, S. G. et al.: Astronomy & Astrophysics, Volume 487, Issue 1, 2008, pp.373-381
4. Sousa, S. G. et al.: Astronomy & Astrophysics, Volume 577, id.A67
5. Sousa, S. G.: ARES+MOOG: A Practical Overview of an Equivalent Width (EW) Method to Derive Stellar Parameters in Determination of Atmospheric Parameters of B-, A-, F- and G-Type Stars, Series: GeoPlanet: Earth and Planetary Sciences. Springer International Publishing (Cham), Edited by Ewa Niemczura, Barry Smalley and Wojtek Pych (2014)