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Determination of stellar parameters

Computational Astronomy - Project I

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ABSTRACT

Context. Spectroscopic data analysis is fundamental for the study of astronomical systems, since it is the main tool for the determination of parameters that allow us to describe them.
Aims. We aimed to develop a concise and efficient method for the determination of atmospheric stellar parameters such as effective temperature, surface gravity, metallicity and chemical abundances. This method is used for the study of two stellar spectra.
Methods. We estimate the parameters by using the equivalent width method though synthetic spectral fitting.
Results. An algorithm that performs automatic stellar spectral analysis is provided and limitations discussed.

Key words. stellar parameters – spectroscopy

1. Introduction

One of the goals of astronomy is the classification of star systems. A core element for this is the study of stellar spectra, from which we gather sufficient information that allow us to obtain parameters that describe these systems.
On this day and age, we have a tremendous and increasing amount of spetroscopic data available, each spectra needing to be carefully analyzed. It would be wise to develop a method that allows us to automatically perfom this analysis.

Here we will be using a dabatase of synthetic spectra, directly comparing them with observed data, together with the equivalent width technique.

The first step is to estimate the excitation temperature, in order to reduce the amount of spectra we compare. The curve of growth for FeI lines is used to estimate this temperature, T_{est}. Then, in a range of$[T_{est} - 400, T_{est} + 400]K$, we compare the star's W_λ values to the corresponding ones of synthetic spectra, finding this way the best fit to the observed data.
After finding the closest synthetic spectrum, we re-sample it performing an interpolation, and apply resolution degradation through the introduction of an instrumental profile, so as to directly and graphically evaluate the quality of our results.

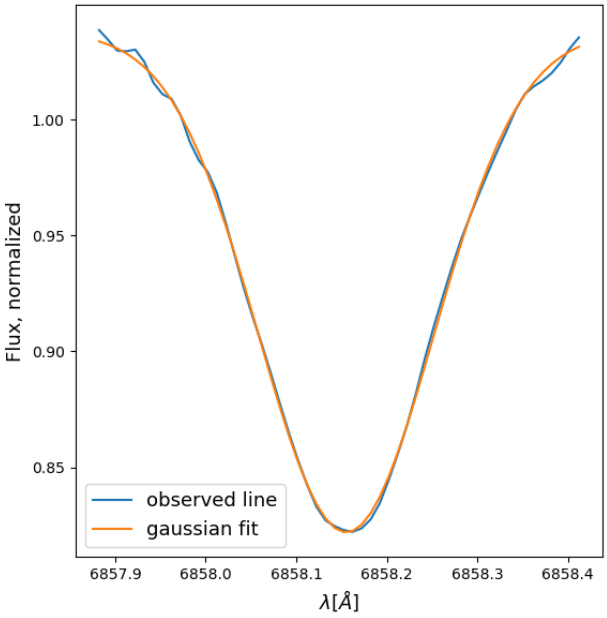

Fig. 1. Example of a gaussian fit of a line found in the spectrum of the first star studied

2. Method

2.1. Preliminary estimation of temperature

2.1.1. Equivalent width determination

For a first estimation of the temperature, we will need to calculate the equivalent width of the spectral lines we wish to study. The equivalent width is given in equation (1), as in ((2)):

$$W_\lambda = \int \frac{F_c - F_\lambda}{F_c} d\lambda = \frac{\sqrt{2\pi} A \sigma}{B} \quad (1)$$

So we can obtain Wλ by fitting a gaussian curve to each line and obtaining the parameters A, B and σ. To perform this, one must first estimate where the lines begin and end. Here the delta method is used, where one estimates a value δ [1] , after a series of

[1] An alternative method to check where the lines start and end would be through the first and second derivatives, however, for these particu-

visual comparisons, for the typical length of the lines in question. This value is then optimized, as will be discussed below.

2.1.2. Growth curves

We then use W_λ to trace the growth curve, plotting $log(W_\lambda/\lambda)$ as a function of $log(gf\lambda)$. The temperature can given by the distance between multiplets (equation 2) as found in (Monteiro et al.2019)):

$$T = \frac{|5040(\chi_1 - \chi_2)|}{\Delta} \quad (2)$$

Where χ_1, χ_2 are the average excitation energies for each multiplet, and Δ the distance between them.

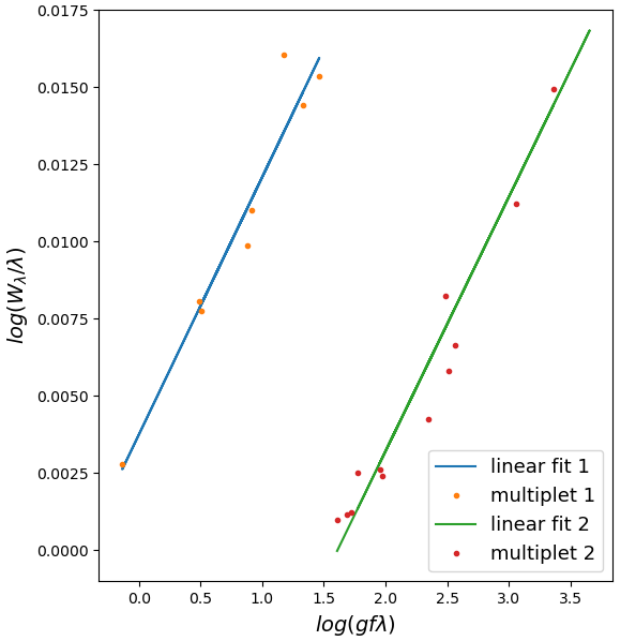

Fig. 2. Example of two solar multiplets, for $\chi_{1,2}$=([2.1,2.3],[4.2,4.3]). Linear fits are also represented

We chose to estimate Δ with the help of linear fittings (curve fittings, yet again!), obtaining the slope and y intercept for each multiplet. Firstly, we see where they have the same Y (ie, $log(W_\lambda/\lambda)$), calculate Δ for its minimum and maximum, then take an average of that value.

It is important to choose multiplets that have different enough excitation energy values, and for which we have the most number of lines.

In order to validate our algorithm, we use it to estimate the temperature of the sun, resulting in $T_{Sun} = 5635K$ and corresponding to an error of 2%.

The purpose of this preliminary estimation is only to limit the range of our study, so a 2% error is completely acceptable.

2.2. Determining the closest synthetic stectrum

The next and maybe the most important step in this work is the actual data comparison.

lar cases it was found, through plotting the fits that use the δ method described above, that they were generally good enough.

In short, we directly compare W_λ values for the observed and synthetic spectra. This is not an easy task, as it is later discussed in this report.

2.2.1. Finding the best fit

In theory, this is very straightforward: for each λ, values of $W_{\lambda,obs}$ and $W_{\lambda,synth}$ are calculated and compared.
Synthetic spectra found on (4) are used for this study, in a range of $T \in [T_{est} \pm 400]K$.
These synthetic spectra are generated for different values of $T, log(g)$, metallicity and chemical abundance. This means that, through this comparison, we'll determine all these parameters.

The algorithm returns the file whose $W_{\lambda,synth}$ are the closest to $W_{\lambda,obs}$ by plotting $W_{\lambda,synth}$ as a function of $W_{\lambda,obs}$ and finding the linear fit whose slope is closest to one. Although this method has its advantages, [2] one must be careful not to choose a fit whose slope is close to unity, but with way too scattered points around it - so a plot of this scheme is needed for further confirmation of the obtained results.

2.2.2. Visual comparison and analysis

The next step is to process the determined synthetic spectrum. We start by applying the instrumental profile, ie, degrading the spectral resolution. This is done by convolving the fluxes with a Gaussian of parameters determined by ((Monteiro et al.2019))):

$$\sigma = \frac{\Delta\lambda}{\sqrt{2ln(2)}} \quad (3)$$

Where $\Delta\lambda =< \lambda > /R$, R being the intrument's resolution. In this case, an $R \approx 50000$ is used ((1)).

Then, re-sampling is done, by using a linear interpolation, which evaluates the synthetic spectrum on the observed spectrum's λ values.

The last step for the processing is estimating the rotational velocity $vsinI$ by computing a fourier transform on spectral lines and analyzing its minima. We can estimate this velocity through the following equation ((Monteiro et al.2019))):

$$vsinI = \frac{\Delta\lambda_M}{\lambda_0} c \quad (4)$$

c being the speed of light and λ_M obtained by comparison with values for the sun.

After estimating the rotational velocity, if this value is found to be significant, we'll need to to another convolution, applying this way a rotational profile. The final simulated spectrum is obtained convolving with a function given by:

$$G_\epsilon(\lambda - \lambda_0) = \frac{2(1-\epsilon)\left(1 - \left(\frac{\lambda-\lambda_0}{\Delta\lambda_M}\right)^2\right)^{1/2} + \frac{\pi\epsilon}{2}\left(1 - \left(\frac{\lambda-\lambda_D}{\Delta\lambda_M}\right)^2\right)}{\pi\Delta\lambda_M(1-\epsilon/3)} \quad (5)$$

3. Implementation and results

It is necessary to chose which lines are going to be used. Here, we worked with the lines found in (1). This reference also provides us with other data we'll need on this work, for example

[2] This comparison could have been done through the least squares method. We choose this approach instead, and the reasoning behind it is to prevent false results due to difference in the amount of data points for each multiplet.

$log(g)$, excitation energy and also W_λ values for the su, the latter which we used in section 2.1 to test our algorithm.

Table 1. Excerpt of data taken from (1)

λ(Å)	EP (eV)	log(g)	El	EW$_{sun}$(mÅ)
4523.40	3.65	-1.871	FeI	44.2
4537.67	3.27	-2.870	FeI	17.4
4551.65	3.94	-1.928	FeI	29.1
4556.93	3.25	-2.644	FeI	26.3
4566.52	3.30	-2.156	FeI	46.2

3.1. Observations

1. While the calculations of W_λ, through the Gaussian fitting and δ method described above, for the observed spectra works smoothly, for the synthetic spectrum it results in errors. This is because, for example, these synthetic spectra not always have lines on the λs we're evaluating, due to their partial overlapping or to high rotational velocity. For the first star studied, however, it was seen that this isn't much of a problem, since our final result is seen to match quite well.
   A better option to compare synthetic spectra would be to determine where the lines start end end through an adaptative method using the first and second derivatives, limiting the line around it's maximum and determining this way its equivalent width. This method, for the observational data requires its further treatment, due to observational noise.

2. Given the Gaussian fit method implemented has adaptative intial conditions, it is safe to say that those that result in errors or that don't have a small enough s value aren't gaussian in behaviour. We can then simply ignore them and only compare equivalent widths of the remaining lines.

3. It was seen that multiplet selection greatly influences the results. For example, choosing $\chi_{1,2} = ([2.1, 2.3], [4.6, 4.7])$ leads us to a $T_{est,Sun} = 5447K$. Some multiplet lines have very different slopes, leading us to a worse distance estimation.
4. Since we ignore some of the lines, the number of equivalent widths we compare for different synthetic spectra aren't always the same. This means that directly employing the least difference method isn't ideal . Evaluating the slope of $W_{\lambda,synth}$ as a function of $W_{\lambda,obs}$ is independent of the number of lines evaluated, therefore being a better option.
5. For the first star, the spectrum is normalized however, for the second case studied, continuum estimation is an issue to be addressed. In general one may find different continuum levels for different wavelengths. A quick way of normalizing each individual line is to perform a gaussian fit of the form $aexp[(x-b)^2/2c^2] + d$, taking the parameter d as the continuum.

3.2. Results

3.2.1. Star 1 - HD17051

For the first case, the multiplets $\chi_{1,2} = ([2.1, 2.3], [4.6, 4.7])$, were used to obtain the growth curves and the preliminary temperature, and are shown in figure 3. Which allowed an estimation of $T = 5954K$.

Plugging in this temperature in our algorithm that limits the browse our database, equivalent width fittig was performed, corresponding to figure 7, leading to the results in table (2).

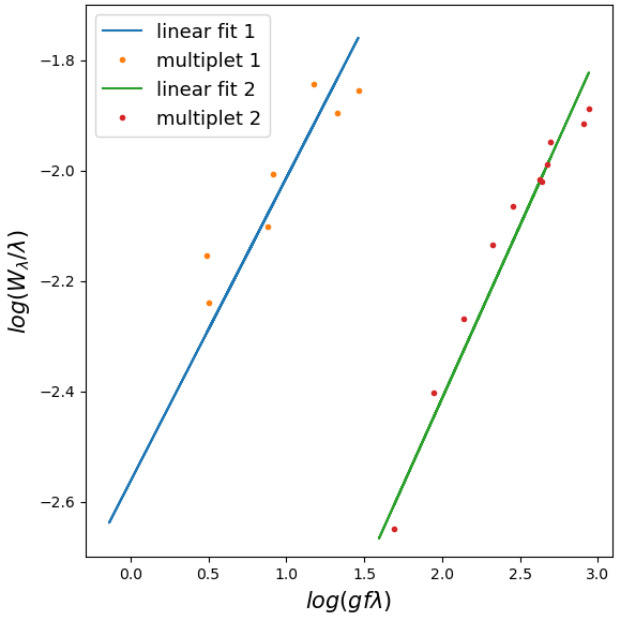

Fig. 3. Multiplets - star 1. Here the same excitation energy range was used as the case for the Sun. These growth curves allowed a first temperature estimate of T = 5954 K

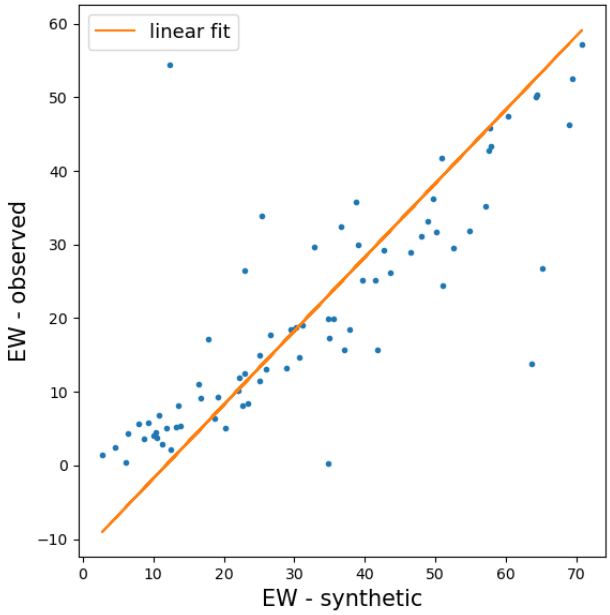

Fig. 4. First star: equivalent width comparison - observed vs best obtained fit. In general the points follow the fit line and aren't significantly distanced from it. However, there is some scattering of the points, and a small zone around the bottom left corner whose center doesn't align perfectly with the linear fit, indicating this may not be the perfect fit.

We may see, through visual comparison, that not all lines match perfectly, and the reason may be that our algorithm isn't as optimized as it could be, however this seems to be a good first

Table 2. Determined parameters for the first star. The temperature estimation is correct, bearing in mind that the files in our database are spaced from one another by T=150K. The obtained log(g) value isn't too far off, either, but could be 4.5 (there's space of 0.5 between log(g) values). There is, however, some significant difference in the result for metallicity, which means this is still probably not the best fit in our whole database, and that the algorithm provided is not fully optimized. Data is from (5)

	T (K)	log(g)	[Fe/H]	α
Obtained	6000	5.00	0.25	0.00
Expected	6122	4.37	0.25	–

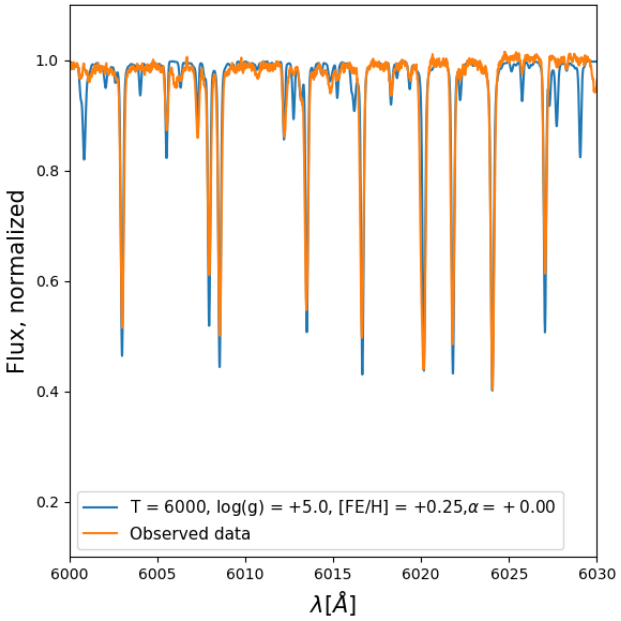

Fig. 5. Spectrum comparison for the first star. It can be seen that a reasonable fit was obtained. Some lines don't match perfectly, as one may notice, but the results are a good first estimate.

initial estimation. Improvements will be discussed in section 4. It was also found that this star has no significant rotational velocity.

3.2.2. Star 2 - HD17051

For the second star, using the same multiplets as for the first star, a rough first temperature estimate of $T = 5309K$ was determined. Equivalent width comparison is represented in figure (7). The final results are shown in figure (8).

Table 3. Determined parameters for the second star. Although the initial temperature estimate is quite good, both log(g) and metallicity values are inaccurate. This aligns with how sparse the equivalent width comparison is, as shown in a figure below. Data from (6)

	T (K)	log(g)	[Fe/H]	α	vsinI
Obtained	5250	5.00	0.50	0.00	6
Expected	5506	4.37	0.25	–	5.2

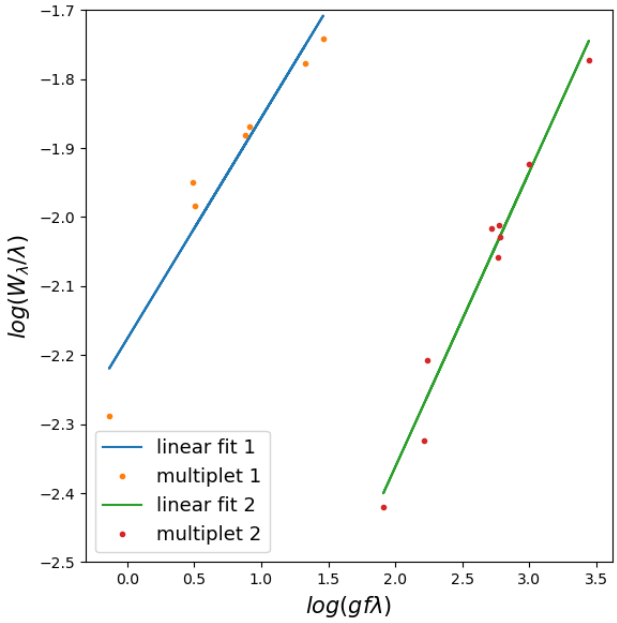

Fig. 6. Multiplets used for the second star. Here the potential energy range used was $\chi_{1,2} = [2.1, 2.3], [4.6, 4.7]$). These growth curves allowed a first temperature estimate of T = 5309 K.

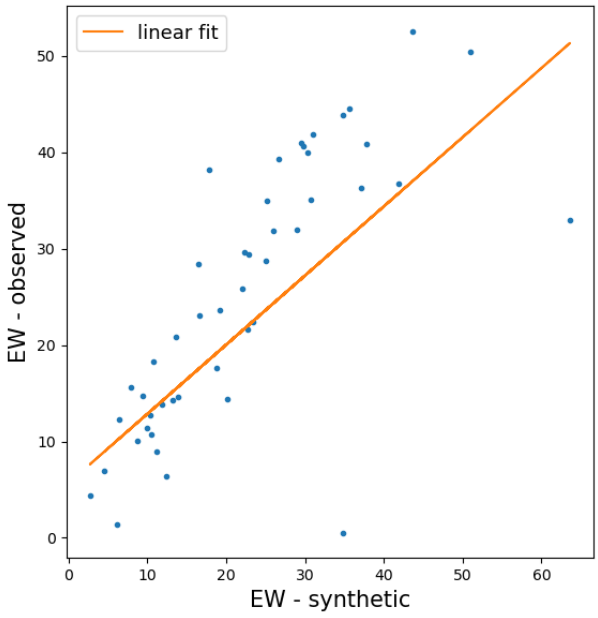

Fig. 7. Second star: Equivalent width comparison - observed vs best obtained fit. Although the temperature obtained is good, since the other parameters will also influence the equivalent width of the spectral lines, one may see that here the points are significantly more scattered around, in comparison to the plot for the first star. This suggests our algorithm should be revised, and a search for a better fit performed.

4. Discussion and Improvements

After looking at our results, one must say a more extensive search could have been performed, and the code optimized in a number of ways.

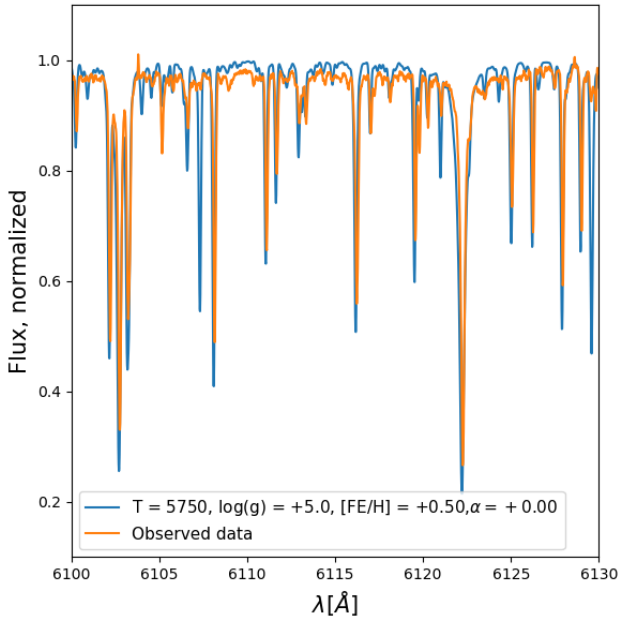

Fig. 8. Spectrum comparison for the second star. This fit is considerably worse, as one may notice. One reason for this can be the spectral line broadening due to significant rotational velocity found in this case, worsening the estimation of the limits of each line.

- Comparison of the equivalent width through the slope method is good, however, one should also search within a range of slopes close to unity, and not only take the closest value as final result. This is, as discussed above, because points can be scattered, influencing the calculation of the slope, leading to a false estimation of the best fit. One should look within a range close to unity, and choose the plot whose points are the least scattered. In a way, this was performed in a number of attempts, but could easily be implemented in our code. An additional estimation of the distance between points could be done automatically, and the fit only accepted within a certain tolerance.
- The calculation of the equivalent widths of the synthetic spectra could be, as mentioned above, performed in a more efficient, clever way, through the use of first and second derivatives. This was not adopted, being certainly one of the sources of error in this algorithm.
- Another improvement would be to find a better method to estimate the continuum for each line. In the first case, this wasn't an issue since its observed spectrum was normalized. However, this probably also affected the results for the estimation of the best fit in the second case.

5. Conclusions

- A code was developed to determine stellar parameters. The method used was the equivalent width method, in which these values for observed and synthetic spectra are directly compared.
- For the first star, it performed quite well, leading to a result that seems to be somewhat successful.
- For the second case, this generally is not analogous, it was seen that the algorithm provided could be further optimized and modified, as discussed above.

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