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Characterization of hot solar-type stars with exoplanets

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ABSTRACT

Aims. The goals for this project were to obtain a general method for spectral analysis to determine stellar atmosphere parameters of hot solar-type stars with exoplanets using the spectral analysis software iSpec**?**. We use this method to determine the stellar atmosphere effective temperature, surface gravity, metalicity, alpha element abundance, microturbulence, macroturbulence and projected rotational velocity.

Methods. Using iSpec we treat all spectra correcting their radial velocity and normalizing. Using a list of the FeI and FeII iron lines we execute an initial synthetic spectra fit, reducing the initial line list. Using the reduced line lists we derive stellar atmosphere parameters following the MARCS atmosphere models and using the spectral analysis codes Turbospec, Synthe and MOOG.

Results. We reached 2 reduced line lists and derived the stellar parameters for all 6 stars. We tested and obtained a general and consistent spectral analysis procedure for hot solar-type stars with exoplanets such that it can be easily reproducible. We analysed and derived stellar parameters for the stars HD 1666, HD103774, HD11231, HD 156846, WASP-101 and WASP-190.

Key words. Exoplanets – Spectroscopy – Stellar Parameters – iSpec

1. Introduction

The spectra of stars is a commonly used mean to study its characteristics and properties. Throughout the years several tools for spectral analysis have been developped in order to derive these properties with greater accuracy, efficiency and consistency. This analysis is done by relating the shape of the absorption lines with a set of stellar parameters that accuratly matches the observed spectra. Within this area there are different approaches on how to process the data. One of these methods, which was used in this work, is the spectral synthesis method. This method consists of producing a synthetic theoretical spectrum using a set of stellar parameters. A final result is obtained when the synthetic spectrum matches the observed one, returning the corresponding parameters for that star. This process can however become harder for hot stars with high rotational velocity, since absorption lines are more likely to overlap thus creating a less clear spectrum to fit. The process of creating synthetic spectra and searching for the best fit is done computationally, existing many codes for the job. In this project we intended to compare different codes using the spectral analysis software, iSpec **?**, for hot solar-type stars with exoplanets, in order to determine the parameters: effective temperature (T_{eff}), surface gravity ($\log(g)$), iron abundance ($[Fe/H]$), microturbulence (ξ), alpha abundance ($[\alpha/Fe]$) and the projected rotational velocity ($v\sin(i)$).

2. Principles of Spectroscopy

The basis of spectrospocy date back to Newton's prism, where a beam of light can be decomposed into its continuum of frequency components. For our purposes, the light emitted from stars can be decomposed into their respective signature spectra. The multiple absorption lines can provide information of the stars parameters, given these relate with the depth and width of the lines. Stars with a high effective temperature and projected rotational velocity present a challenge for spectral analysis, since the broadening of the lines is higher resulting in the merging of consecutive lines. Most codes struggle in such situations as it becomes much more difficult to distinguish individual lines and to determine a clear set of parameters that matches the observed spectrum. In order to obtain trustworthy results a sequence of procedures must be taken to minimize the sources of error and ambiguity. All these steps were done using iSpec for each of the spectra analysed throughout this work.

3. Data preparation

3.1. Importing data and errors

The spectra was viewed and analysed using iSpec. From the provided spectrum, in some cases, we defined the errors in the software. This estimate is based on the signal to noise ratio (SNR), which can be calculated directly from iSpec through a designated function. Having the values of SNR, represented in table 1 we set the error for each point as the invserse of the SNR multiplied by the flux at that point. This operation can also be done within iSpec. We analysed the spectra of 6 stars, all hosting 1 known exoplanet each[1]:

- HD1666, spectral type F7
- HD103774, spectral type F5
- HD11231, spectral type F5
- HD156846, spectral type G0
- WASP-101, spectral type F6
- WASP-190, spectral type F6

[1] exoplanet.eu

All spectra was obtained by the spectrograph HARPS, which has a resolution of 115000 in the wavelength range of 383 to 693 nm (which contains the ranges used throughout this work).

Table 1: SNR values for studied stars determined within iSpec.

	HD 1666	HD 103774	HD 11231	HD 156846	WASP-101	WASP-190
SNR	120	800	365.54	309.58	221.79	109.08

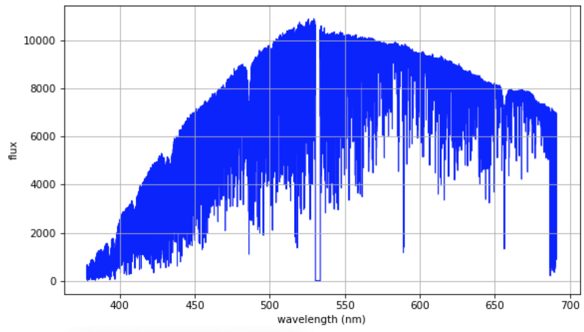

Fig. 2: Spectra of HD 1666 before being reduced and normalized.

3.2. Defining continuum and line regions

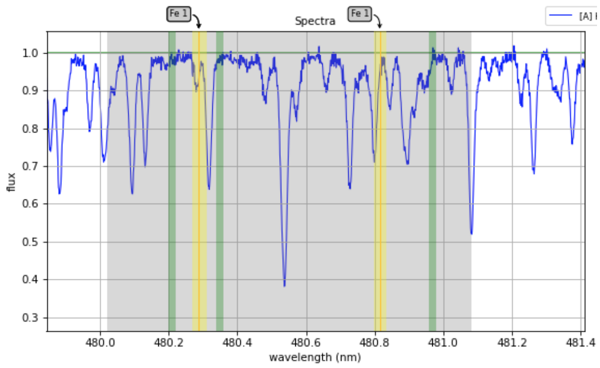

Fig. 1: A section of the spectrum visualized on iSpec, with the segment in gray, line regions in yellow (corresponding to 2 *FeI* lines as stated by the labels) and continuum regions in green.

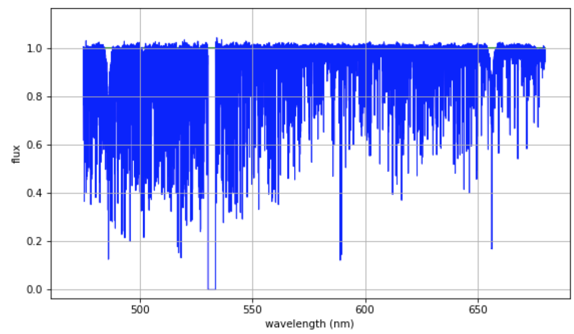

Fig. 3: Spectra of HD 1666 after reduced and normalized using 60 splines and a wavelength step of 0.05 nm for median selection and of 4 nm for maximum selection.

Upon opening the spectrum to be analysed we used a list of known lines of an element or a set of elements. We used the lines corresponding to atomic iron *FeI* and ionized iron *FeII*, as well as a list of continuum regions (regions without any lines). In iSpec both must be inserted into segments, as shown in figure 1. All these lists are provided after downloading the software. Since the spectra was measured by HARPS there is a zone between 530.466 and 533.759 nm. The line and continuum lists used only cover a portion of the full spectra, so we cropped it to leave only the data between 475 to 680 nm. This reduction doesn't affect the fitting since the codes used only evaluate the fit in the line regions. Outside the line regions the differences between the fit and the data doesn't matter, however reducing the wavelength range can help with the normalization of the spectra.

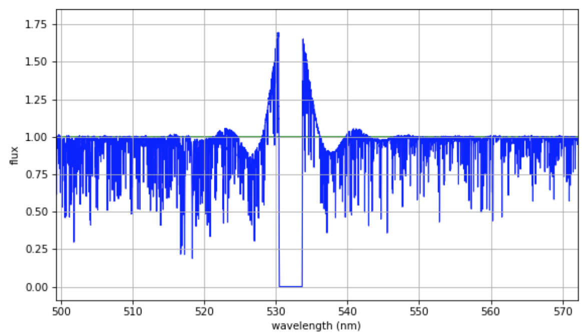

Fig. 4: Bad normalization in the spectrum of HD 103774 near the section without data.

3.3. Normalization of spectrum

Once the spectra is ready to be analysed it must be normalized to correctly measure the characteristic quantities of the absorption lines (width, depth, etc.). Normalization consists of dividing every wavelength point by the theoretical flux if there were no lines, such that the continuum is fixed at flux=1, and the lines all fall below this value.

Since the continuum isn't a perfect black body we determine it by approximating the curve with splines. iSpec has a function for fitting the continuum using splines, as well as other methods, and suggests, based on the data, the parameters of the fit. Using the default parameters, however, results in a bad fit around the region without data for some of the stars, as can be seen in figure 4, for example.

For all spectra we fit the continuum with 60 splines and a wavelength step of 0.05 nm for median selection and of 4 nm for maximum selection. The remaining parameters were left as defaultly presented. This allows for a smooth continuum fit, even near the area without data, which previously did not normalize correctly. The following step is to correct the velocity relative to the atomic lines. Due to the movement of the star, the absorption lines can present a shift in their central wavelength relative to the expected value for each peak. From this shift we can estimate the velocity of the star and correct for that value. From iSpec this estimate can be made using all default parameters, which yields the values in table 2.

Table 2: Mean velocity and error relative to atomic lines estimated by the deviation between the peak central wavelegth and the expected wavelength.

	HD1666	HD103774	HD11231	HD156846	WASP-101	WASP-190
mean v (km/s)	17.85	-3.07	7.47	-68.27	42.65	1.05
error (km/s)	0.04	0.07	0.05	0.03	0.12	0.18

4. Synthetic spectrum fitting

4.1. Initial parameters

Creating a synthetic spectra envolves an iterative χ^2 minimization process, thus the initial parameters must be inputted prior to the fitting. Since we are using spectra from HARPS we used a fixed resolution of 115000, leaving the values for T_{eff}, $\log(g)$, $[Fe/H]$, ξ, $[\alpha/Fe]$ and $v\sin(i)$ free to vary from the default values filled by iSpec, and determining the macroturbulence v_{mac} using the empyric formula shown in equation 1. The limb darkening coefficient was treated as fixed at 0.6 for all stars. For all codes and stars we used the MARCS model atmospheres, returning the stellar parameters after 6 iterations. The computational time for these conditions varies from code to code, taking approximatly 10 minutes for MOOG and between 1 and 2 hours for Turbospec and Synthe.

$$v_{mac} = 3.21 - 2.33 \times 10^{-3}(T_{eff} - 5777) + 2.00 \times 10^{-6}(T_{eff} - 5777)^2 - 2(\log(g) - 4.44) \tag{1}$$

4.2. First fit and line selection

It is essential to select the lines more suitable for the synthesis, as some of them may be overlapping neighbour lines or have too much noise and an unclear shape. We executed a first synthesis using the codes Turbospec, Synthe and MOOG, using the full iron line list and from the resulting synthetic spectrum evaluated individually the lines to be removed. Once the line list has been filtered we run the codes once more.

It is possible, and was the case for some stars such as WASP-101, that the first fit does not return results for some codes, if not all. This happens for spectra that are very hard to read, with many overlapped lines and noisy data. In this case we must filter the lines by viewing the observed spectrum and judging if each line is well defined and isolated. Examples of cases where lines were removed are ilustrated in figure A.1 in the anexes.

The procedure of reducing the line list after a first fit was done for stars HD 1666 and HD 103774, individually treated, resulting in 2 slightly different reduced line lists. Using a python script and the 2 line lists, we can create a new line list containing the common lines between the originally provided lists, which will be equal or smaller than these.

4.3. Reduced line lists

Using the line list created from intercepting the HD 1666 selection and HD 103774 selection we can now use it to obtain the stellar parameters of the remaining 4 stars, as well as test if this list is capable of returning satisfactory results. In cases where the list failed to return resusts for more than one code, we executed yet another selection process. This was the case for WASP-101, for which after reducing we obtained the second reduced line list.

5. Results

Using codes Turbospec, Synthe and MOOG and the first and second reduced line lists, we were able to reach the results presented in tables 4 to 9. For reference we present in table 3 the values reported in the SWEET-Cat catalogue **?**.

For each fit, we present the χ^2 and the RMS errors. The lines without values represent cases where the code failed to fit the spectrum. WASP-101 showed to be a particular challenging spectrum since no code was able to fit the spectrum using the first line list, as verified from table 8, thus the necessity for a second reduction. From tables 8 and 9 we notice Synthe was not able to fit for any line list. This can show this code does not perform as well for stars with a very high rotational velocity. In all cases Turbospec returned results, showing to be a more stable code. MOOG doesn't fall short, only failing for HD 103774. All successfull runs present a χ^2 below 5 and an RMS below 0.025. The general uncertainties are below those from the reference values in table 3.

Table 3: Reference values for T_{eff}, $\log(g)$, $[Fe/H]$ and ξ reported in SWEET-Cat**?**.

	T_eff (K)		log(g) (dex)		[Fe/H] (dex)		ξ (km/s)	
	value	error	value	error	value	error	value	error
HD 1666	6508	30	4.29	0.03	0.39	0.02	1.77	0.03
HD 103774	6586	35	4.48	0.03	0.31	0.02	1.72	0.02
HD 11231	6643	35	4.32	0.04	0.19	0.02	1.96	0.04
HD 156846	6152	20	4.16	0.04	0.23	0.02	1.45	0.02
WASP-101	6604	50	4.77	0.04	0.31	0.03	1.84	0.07
WASP-190	6730	55	4.52	0.07	0.15	0.04	2.07	0.09

6. Conclusions

We present the stellar atmosphere parameters for the 6 hot solar-type stars with exoplanets using a general method for the spectral analysis through the software iSpec and the codes Turbospec, Synthe and MOOG. Turbospec presented to be the most stable code with the least failure rate and Synthe showed higher failure for stars with very high rotational velocity.

We defined 2 line lists composed of a selection of FeI and FeII iron lines for general use with the synthesis method for hot solar-type stars with high rotational velocity. The results were obtained using a consistent and homogenous data treatment and analysis, thus making them easily reproducible.

7. References

Acknowledgements. This project was supervised by Sérgio Sousa and Elisa Mena

Table 4: Results obtained for HD 1666 with the first reduced line list (top table) and for the second reduced line list (bottom table).

		T_eff (K)		*log(g)* (dex)		[Fe/H] (dex)		[α/Fe] (dex)		ξ (km/s)		*v_mac* (km/s)		*vsin(i)* (km/s)		χ2	RMS
		value	error	value	error	value	error	value	error	value	error	value	error	value	error		
First reduced	**Turbospec**	6432.85	64.3	4.01	0.08	0.32	0.03	-0.04	0.11	1.73	0.06	6.46	empyrical	5.34	0.26	4.89	0.0239
	Synthe	6406.23	57.63	3.92	0.08	0.31	0.03	0.01	0.1	1.72	0.06	6.51	empyrical	5.3	0.28	4.93	0.024
	MOOG	6649.54	43.79	4.24	0.07	0.44	0.03	0	0.12	1.81	0.06	7.17	empyrical	4.53	0.26	5.13	0.0244
Second reduced	**Turbospec**	6570.69	88.43	4.13	0.12	0.39	0.04	0.02	0.11	1.75	0.08	6.93	empyrical	4.72	0.45	3.29	0.0221
	Synthe	6454.94	90.01	4.01	0.07	0.34	0.04	0.03	0.1	1.72	0.09	6.57	empyrical	5.23	0.21	3.67	0.0233
	MOOG	6712.3	77.67	4.29	0.1	0.48	0.04	-0.04	0.13	1.81	0.07	7.44	empyrical	4.2	0.54	3.59	0.023

Table 5: Results obtained for HD 103774 with the first reduced line list (top table) and for the second reduced line list (bottom table).

		T_eff (K)		*log(g)* (dex)		[Fe/H] (dex)		[α/Fe] (dex)		ξ (km/s)		*v_mac* (km/s)		*vsin(i)* (km/s)		χ2	RMS
		value	error	value	error	value	error	value	error	value	error	value	error	value	error		
First reduced	**Turbospec**	6549.8	33.64	4.21	0.04	0.24	0.02	-0.12	0.06	1.62	0.04	6.67	empyrical	8.56	0.11	1.99	0.0152
	Synthe	6481.22	30.7	4.1	0.04	0.23	0.02	-0.13	0.05	1.61	0.04	6.52	empyrical	8.65	0.1	1.93	0.015
	MOOG	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Second reduced	**Turbospec**	6677.77	46.59	4.3	0.06	0.31	0.02	-0.08	0.06	1.66	0.05	7.21	empyrical	8.23	0.17	1.17	0.0132
	Synthe	6534.31	41.03	4.13	0.04	0.25	0.02	-0.09	0.05	1.64	0.05	6.73	empyrical	8.53	0.15	1.31	0.0139
	MOOG	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-

Table 6: Results obtained for HD 11231 with the first reduced line list (top table) and for the second reduced line list (bottom table).

		T_eff (K)		*log(g)* (dex)		[Fe/H] (dex)		[α/Fe] (dex)		ξ (km/s)		*v_mac* (km/s)		*vsin(i)* (km/s)		χ2	RMS
		value	error	value	error	value	error	value	error	value	error	value	error	value	error		
First reduced	**Turbospec**	6598.11	21.03	4	0.03	0.14	0.01	-0.08	0.05	1.85	0.02	7.35	empyrical	6.41	0.09	2.71	0.0178
	Synthe	6562.3	19.37	3.92	0.03	0.13	0.01	-0.04	0.04	1.82	0.02	7.3	empyrical	6.45	0.09	2.71	0.0178
	MOOG	6722.11	26.7	4.15	0.03	0.2	0.01	-0.03	0.04	1.89	0.03	7.77	empyrical	6.09	0.15	2.94	0.0185
Second reduced	**Turbospec**	6742.94	26.32	4.15	0.03	0.21	0.01	-0.02	0.04	1.89	0.03	7.9	empyrical	5.8	0.18	1.76	0.0161
	Synthe	6637.78	26.71	4.01	0.03	0.17	0.01	-0.01	0.04	1.85	0.03	7.56	empyrical	6.18	0.16	1.99	0.0171
	MOOG	6999.71	28.06	4.49	0.03	0.32	0.01	0	0.04	1.93	0.03	8.95	empyrical	4.23	0.28	2.09	0.0176

Table 7: Results obtained for HD 156846 with the first reduced line list (top table) and for the second reduced line list (bottom table).

		T_eff (K)		*log(g)* (dex)		[Fe/H] (dex)		[α/Fe] (dex)		ξ (km/s)		*v_mac* (km/s)		*vsin(i)* (km/s)		χ2	RMS
		value	error	value	error	value	error	value	error	value	error	value	error	value	error		
First reduced	**Turbospec**	6070.09	9.4	3.95	0.01	0.16	0.01	0.03	0.02	1.45	0.01	5.05	empyrical	3.98	0.03	4.08	0.0218
	Synthe	6081.68	11.29	3.9	0.02	0.15	0.01	0.13	0.01	1.45	0.01	5.19	empyrical	3.92	0.05	4.31	0.0224
	MOOG	6197.92	10.18	4.09	0.01	0.23	0.01	0.13	0.02	1.46	0.01	5.25	empyrical	3.83	0.04	4.29	0.0224
Second reduced	**Turbospec**	6125.8	14.81	4.04	0.02	0.19	0.01	0.08	0.01	1.41	0.01	5.07	empyrical	3.92	0.05	2.86	0.0206
	Synthe	6174.1	14.94	3.95	0.01	0.2	0.01	0.17	0.02	1.48	0.02	5.44	empyrical	3.52	0.08	3.24	0.0219
	MOOG	6266.1	15.25	4.11	0.02	0.27	0.01	0.12	0.02	1.48	0.01	5.48	empyrical	3.48	0.07	3.09	0.0213

Table 8: Results obtained for WASP-101 with the first reduced line list (top table) and for the second reduced line list (bottom table).

		T_eff (K)		*log(g)* (dex)		[Fe/H] (dex)		[α/Fe] (dex)		ξ (km/s)		*v_mac* (km/s)		*vsin(i)* (km/s)		χ2	RMS
		value	error	value	error	value	error	value	error	value	error	value	error	value	error		
First reduced	**Turbospec**	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	Synthe	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	MOOG	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Second reduced	**Turbospec**	6599.32	45.71	4.48	0.05	0.26	0.02	-0.01	0.05	1.64	0.05	6.39	empyrical	12.32	0.13	1.01	0.0122
	Synthe	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	MOOG	6706.73	42.46	4.56	0.04	0.33	0.02	-0.06	0.07	1.68	0.05	6.87	empyrical	12.17	0.13	1.12	0.0129

Table 9: Results obtained for WASP-190 with the first reduced line list (top table) and for the second reduced line list (bottom table).

		T_eff (K)		*log(g)* (dex)		[Fe/H] (dex)		[α/Fe] (dex)		ξ (km/s)		*v_mac* (km/s)		*vsin(i)* (km/s)		χ2	RMS
		value	error	value	error	value	error	value	error	value	error	value	error	value	error		
First reduced	**Turbospec**	6552.5	22.77	4.1	0.03	0.03	0.01	0.09	0.03	1.73	0.03	6.9	empyrical	13.48	0.07	1.68	0.014
	Synthe	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	MOOG	6735.48	25.06	4.22	0.03	0.11	0.01	0.09	0.04	1.81	0.03	7.71	empyrical	13.2	0.07	1.71	0.0141
Second reduced	**Turbospec**	6680.01	38.46	4.34	0.5	0.1	0.02	-0.03	0.04	1.66	0.04	7.15	empyrical	13.52	0.08	1.11	0.0128
	Synthe	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	MOOG	6904.91	29.34	4.37	0.03	0.2	0.02	0.08	0.04	1.9	0.03	8.53	empyrical	13.15	0.11	1.13	0.0129

Appendix A: Additional Figures

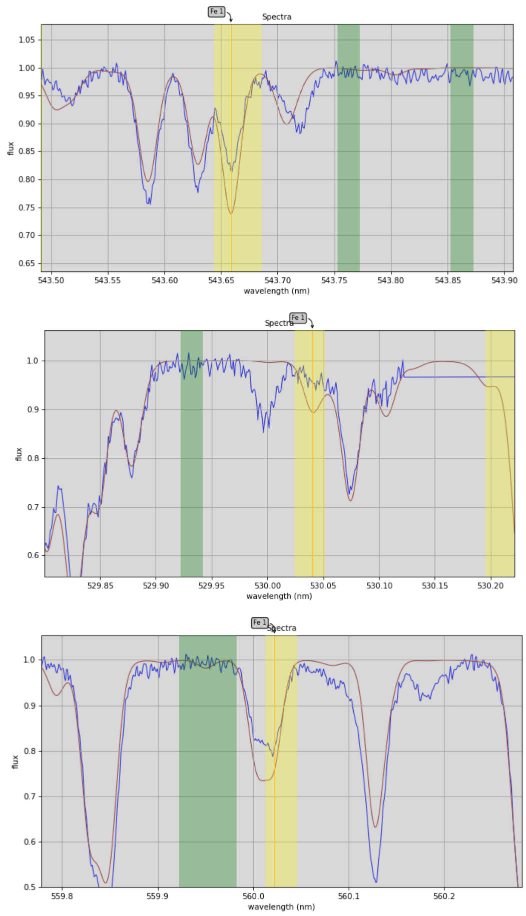

Fig. A.1: Examples from HD 1666 spectrum of excluded line regions due to bad match between fitted line and observed line (top left), very noisy data (top right) and peak overlapping of multiple lines (bottom). The blue graph represents the observed spectrum and the red graph represents the fitted synthetic spectrum.