

On the determination of elemental abundances in three stars

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We analysed spectra of HD 126535 (K1 V), HD 127423 (G0 V) and HD 128356 (K2.5 IV) obtained with the spectrograph HARPS at the ESO La Silla 3.6m telescope in Chile. Our synthetic spectral fitting procedure was firstly verified by analysing the spectra of the Sun and Arcturus, which were used as a template stars with well-known abundances. Comparison of obtained synthetic and observed spectra allowed us to identify 98 spectral lines of 10 chemical elements (Si, Ca, Sc, Ti, V, Cr, Mn, Fe, Co, Ni) within wavelength range $4500 \text{ \AA} < \lambda < 7000 \text{ \AA}$. Abundances of each chemical element in the atmosphere of three studied stars were determined using the equivalent width of identified lines.

Key words: stars: fundamental parameters, stars: abundances, techniques: spectroscopic

INTRODUCTION

According to the modern studies nearly 20% stars with spectra morphologically similar to the solar spectrum host Earth-sized exoplanets with orbit located in the habitable zone. This makes possible the presence of liquid water on their surface, which is a prerequisite of the Earth-like life [18]. Therefore, the determination of physical and chemical parameters of host solar-type stars plays significant role in the study of the necessary conditions for the origin of life on the exoplanets. At the same time, this allows to investigate the possible difference of abundances for single and planet-hosting stars, see [16] and references therein.

The main goal of our study is a determination of elemental abundances in the atmospheres of three solar-type stars HD 126535, HD 127423 and HD 128356. The abundances of 15 elements for these stars have been already calculated in several previous works [13, 15], but more details on these stars are provided in [8], where abundances of 12 different elements were obtained using the synthetic spectra approach.

OBSERVED SPECTRA

Spectra of HD 126535, HD 127423, HD 128356 were obtained with $R = 120\,000$ within wavelength range $3800\text{--}6800 \text{ \AA}$ with the High Accuracy Radial velocity Planet Searcher (HARPS) at the ESO La Silla 3.6m telescope (see Table 1 and [8] for more details). HD 128356 shows the presence of an exoplanet¹. Spectral types of the studied stars lie between the Sun (G2) and Arcturus (K2), which were chosen as our benchmark stars due to their well-known abundances. We used atlas of spectral lines for the Sun ($R \approx 500\,000$) [12], which is based on 50 scans obtained using the solar Fourier-spectrometer at Kitt Peak National Observatory in USA [9]. For Arcturus we used the spectrum from the atlas obtained on the Echelle spectrograph at Kitt Peak National Observatory in USA ($3727\text{--}9300 \text{ \AA}$, $R = 150\,000$, see [7]). All selected lines are presented in Table 2.

Equivalent widths of selected absorption lines were measured using Image Reduction and Analysis Facility (IRAF) [14], which is a universal software package for processing and analysis of astronomical data created at the National Optical Astronomy Observatory (NOAO). For equivalent width measure-

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¹<https://exoplanets.nasa.gov/exoplanet-catalog/7234/hd-128356-b/>

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ment we used **SPLIT** routine, which implements the line profile approximation by the one of pre-selected functions (e.g. Gauss, Lorentz or Voigt) or by the direct integration. Since most of our selected spectral lines show rather weak wings we chose the Gauss profile for the approximations of the line profile.

ABUNDANCE DETERMINATION PROCEDURE

There are at least two main methods for the abundance determination: a reproduction of the absorption by the integral flux of a spectral line (i.e. curve-of-growth method, COG) and an approximation of the observed profile of a spectral line. The first approach requires the set of stellar parameters like effective temperature T_{eff} , surface gravity $\log g$, metallicity $[\text{Fe}/\text{H}]$ and microturbulent velocity v_t be determined or adopted from the theoretical model. At the same time, the second method requires to determine only two additional parameters such as macroturbulent and rotational velocities.

Our method of synthetic spectral fitting depends heavily on a curves-of-growth (COG) approach. By definition, the curve-of-growth is the dependence of the equivalent width EW of a spectral line on the number of absorbing atoms N which form this line. Considering classical Unsöld approximation for EW [20] we obtain dependencies for three types of lines: for weak line (see Eq. (1), saturation of the line's core in Eq. (2) and wings in Eq. (3):

$$EW \sim N g f \gamma, \quad (1)$$

$$EW \sim \sqrt{\log N g f \gamma}, \quad (2)$$

$$EW \sim \sqrt{N g f \gamma}. \quad (3)$$

The g is the statistical weight, the γ parameter is $\gamma = \gamma_2 + \gamma_4 + \gamma_6$, where γ_2 , γ_4 and γ_6 are the constants of a natural, Stark and van der Waals broadenings, accordingly. In the most general case, the accuracy of the COG method is limited mainly by the errors EW measurements and the uncertainties of damping constants γ and oscillator strengths f .

The procedure of the abundances determination was performed using **WIDTH** program [2, 10] following the next steps: (a) selection of unblended spectral lines for abundance analysis; (b) verification of our abundance determination procedure by re-computation of abundances for the Sun and Arcturus; (c) determination of abundances in the atmospheres of HD 126535, HD 127423, HD 128356; (d) comparison of obtained results with those presented in the literature.

To find unblended lines in the solar and Arcturus spectra we computed synthetic spectra by **WITA** software [11, 16] and compared these to the observed spectra (see the next section) Since observed spectra are affected by the instrumental broadening as

well as broadening due to the presence of a rotation and macroturbulence, the proper comparison of the observed and synthetic spectra requires the convolution of the synthetic spectra with the correspondent instrumental profile [4]. Such convolution can be described as the Gauss function:

$$H(\lambda) = \frac{1}{\sqrt{\pi}\alpha} \exp \left\{ \left[- \left(\frac{\lambda - \lambda_0}{\alpha} \right)^2 \right] \right\},$$

where λ_0 is the line central wavelength, and $\alpha = \text{FWHM}/\ln 2$, where FWHM is a full width at half maximum of a line.

RESULTS

We adopt the following criteria for the spectral line selection: the line should be (a) have $EW > 1$ pm, (b) be unblended, (3) be well-fitted with available abundances in both spectra of the Sun and Arcturus. We started from the list of the unblended absorption lines in the solar spectrum presented in [19]. The list consists of 602 unblended absorption lines in the range 4000–7000 Å. Each line was identified in the spectra of the Sun and Arcturus through comparison with synthetic spectra for three abundances of the correspondent element (see Fig. 2): normal abundance [1], reduced abundance ($[A]_{\text{red}} = [A] - 0.3$) and without any absorption (set as $[A] = -10.0$ in **WITA** program). The last case was computed to reveal possible contribution of other elements into formation of the observed feature. In that way we compiled the list #1 of 110 selected absorption lines. Microturbulent velocities v_t were taken as 1 km/s for the Sun [12] and 1.5 km/s for Arcturus [7].

The uncertainty of EW determination is a main source of errors in the derived abundances [4]. To decrease the uncertainty of EW determination it is necessary to estimate continuum reliably in the observed spectra. Firstly, we used continuum for HD 126535, HD 127423 and HD 128356 provided by the HARPS pipeline on broad spectral ranges, but for some lines the local continuum appears to be more reliable than the pipeline's solution. In addition, as the third continuum option we adopted the solar spectrum with custom continuum analyzed by Rutten & Zalm [19]. To obtain a self-consistent set of abundance values, we re-measured EW s in respect to the local continuum in the spectra of the Sun and Arcturus, see Table 2. We found that our abundances in the Sun and Arcturus are consistent with known abundances. Moreover, we discovered that some lines from the list #1 can be well fitted to the solar spectrum, but fail for the Arcturus spectrum and vice versa. Therefore, we compiled the list #2 of 98 lines which represent known abundances both for the Sun and Arcturus (see Table 2).

Relative behavior of equivalent widths of Fe I lines determined in spectra of three studied stars is shown

in Fig. 1. We found that the intensity of Fe I increases with the decrease of effective temperature T_{eff} , which indicates that T_{eff} plays a key role in the formation of this line.

We used the line list #2 to determine abundances in the atmospheres of sample stars. Using the derived abundances from Fe I lines we adopted microturbulent velocities $v_t = 1.0$ km/s in the atmospheres of HD 126535, HD 127423 and HD 128356 (see the abundance values in Table 3). Note, our list of spectral lines and our procedure of the abundance analysis differs from those used by [8]. Likely, the main discrepancy with [8] can be explained by differences in the adopted continuum levels in the observed spectra.

Another possible reason of the differences might be the uncertainty of the adopted oscillator strengths f . In Fig. 3 we show the comparison of gf values from Vienna Atomic Line Database (VALD, [6]) and Gurtovenko & Kostik [5]. A linear fit gradient S is of the order of 0.75, but the exclusion of six outliers increases S up to 0.94. This implies that for the strong spectral lines the gf values from Gurtovenko & Kostik are a better choice.

CONCLUSIONS

As mentioned above, we analyzed spectra of the three solar-type stars – HD 126535, HD 127423 and HD 128356 and derived abundances for Si, Ca, Sc, Ti, V, Cr, Mn, Fe, Co and Ni in their atmospheres. Table 3 shows that elemental abundances in the atmospheres of the studied stars are similar to the values of the corresponding elements in the solar atmosphere. To analyze spectra of studied stars, we used the procedure based on the curve-of-growth method and WIDTH code, which was firstly verified by the analysis of the solar and Arcturus spectra. To get more reliable results we performed a special subtask to select the best 98 unblended absorption lines, which abundances are well-known from spectra both of the Sun and Arcturus. In addition, this procedure allowed us to verify the adopted spectroscopic parameters (e.g. oscillator strength, etc) and enhance the robustness of our procedure.

Despite the differences in abundance determination procedures, our derived abundances (see Table 3) are in good agreement with values derived by [8]. The differences do not exceed 0.2 dex, which means that at least this incoherence between different authors can be explained by the differences in the procedures as was suggested by Ivanyuk et al. (see Fig. 4 in [8]).

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Table 1: The main parameters of the studied stars (see details in [3, 16])

Name	RA	Dec	Spectral class	m(V)	$v \sin i$ (km/s)	v_t (km/s)	[Fe/H]
HD 126535	14 ^h 26 ^m 34.702 ^s	−18°49′12.20″	K1V	8.83 ^m	2.1	1.0	0.10
HD 127423	14 ^h 32 ^m 24.570 ^s	−37°49′02.49″	G0V	8.53 ^m	4.3	1.0	−0.09
HD 128356	14 ^h 37 ^m 04.888 ^s	−25°48′09.26″	K2.5IV	8.26 ^m	1.3	0.8	0.34

Table 2: The abundances for the Sun and Arcturus (in the logarithmic scale) estimated for the line list #2 and local continuum (see the text). The last column shows the final number of lines for different ions in the list #2. The uncertainties are presented as $-4.54(10) = -4.54 \pm 0.10$.

Element	Sun		Arcturus		Number of unblended lines
	this paper	[1]	this paper	[17]	
Si	−4.54(10)	−4.54	−4.63(2)	−4.59	1
Ca	−5.72(3)	−5.66	−5.93(8)	−5.88	4
Sc	−8.88(6)	−8.98	−9.12(2)	−9.24	2
Ti	−7.19(6)	−6.98	−7.24(13)	−7.25	8
V	−8.12(3)	−8.04	−7.74(43)	−8.54	5
Cr	−6.38(7)	−6.44	−6.91(10)	−6.87	7
Mn	−6.63(0)	−6.64	−7.28(0)	−7.15	1
Fe (Fe I)	−4.50(15)	−4.50	−4.91(16)	−4.87	48
Fe (Fe II)	−4.58(4)	−4.50	−5.03(9)	−4.87	6
Co	−7.18(9)	−7.12	−7.36(18)	−7.62	5
Ni	−5.81(10)	−5.82	−6.18(8)	−6.29	11

Table 3: Abundances in the atmospheres of the studied stars. The values computed in this work correspond to the case of a local continuum (‘calc’ columns). The ‘mod’ values are from the model with known value of microturbulent velocities.

Element	HD 126535		HD 127423		HD 128356	
	calc.	mod.	calc.	mod.	calc.	mod.
Si	−4.29(0)	−4.31	−4.46(0)	−4.46	−4.08(0)	−4.03
Ca	−5.63(7)	−5.57	−5.70(7)	−5.72	−5.61(12)	−5.29
Sc	−8.71(1)	−8.89	−8.94(13)	−9.04	−8.51(2)	−8.61
Ti	−7.08(11)	−6.89	−7.28(7)	−7.04	−7.01(16)	−6.61
V	−7.79(10)	−7.95	−8.24(9)	−8.10	−7.53(20)	−7.67
Cr	−6.26(8)	−6.35	−6.39(8)	−6.50	−6.22(10)	−6.07
Mn	−6.41(0)	−6.55	−6.69(0)	−6.70	−6.22(0)	−6.27
Fe (Fe I)	−4.40(17)	−4.31	−4.50(16)	−4.46	−4.28(20)	−4.03
Fe (Fe II)	−4.34(5)	−4.31	−4.54(6)	−4.46	−4.05(16)	−4.03
Co	−7.02(18)	−7.03	−7.23(5)	−7.06	−6.72(17)	−7.00
Ni	−5.65(11)	−5.73	−5.85(13)	−5.76	−5.41(7)	−5.70

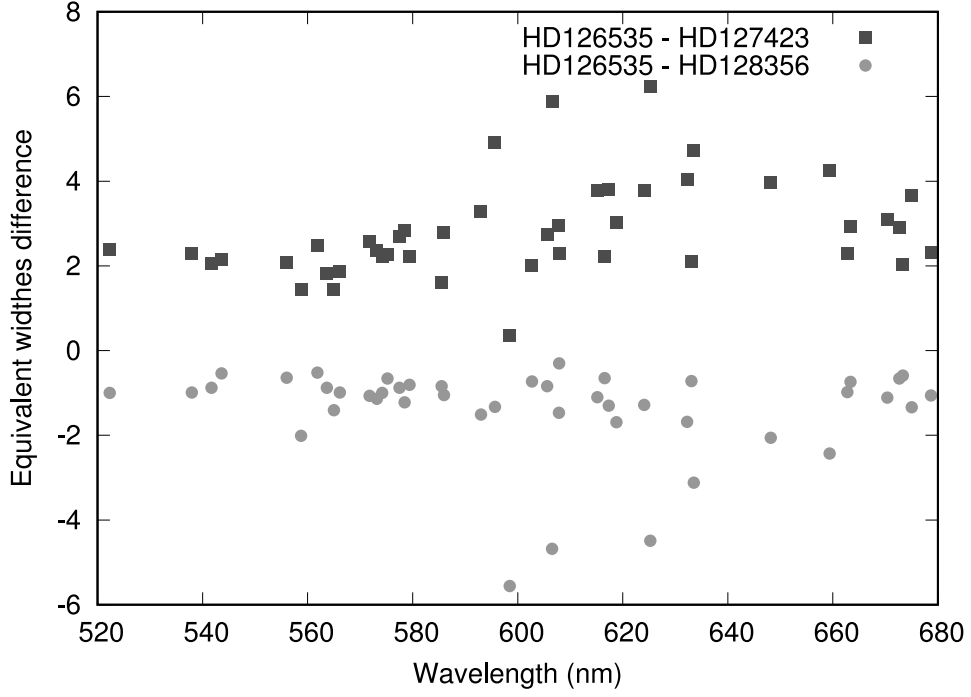


Fig. 1: Relative strength of FeI equivalent widths measured in spectra of HD 126535 ($T_{\text{eff}} = 5284\text{ K}$), HD 127423 ($T_{\text{eff}} = 6020\text{ K}$) and HD 128356 ($T_{\text{eff}} = 4875\text{ K}$).

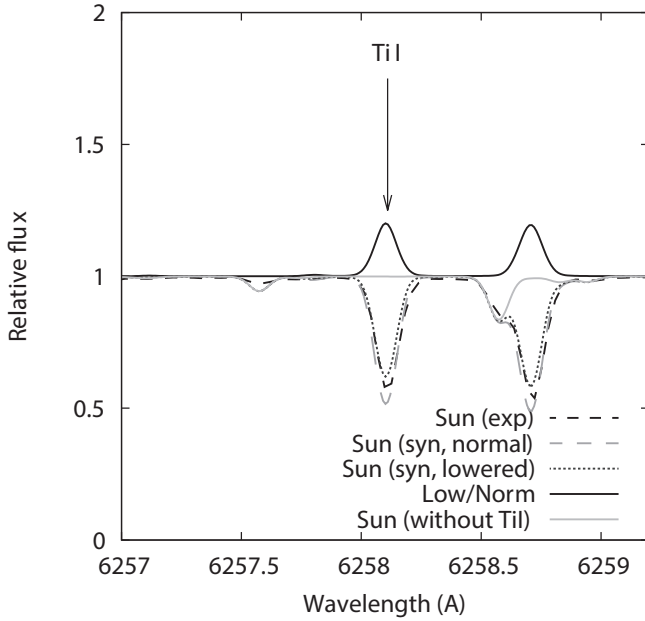


Fig. 2: An example of analysis of neutral Ti line in the solar spectrum (the spectral line is marked with an arrow). Dashed black line corresponds to the observed spectrum. Synthetic spectra with standard, lowered (-0.3 dex) and zero titanium abundances are presented by dashed, dotted and solid grey lines, respectively. The ratio of synthetic spectra with lowered and standard abundances is shown by solid black line.

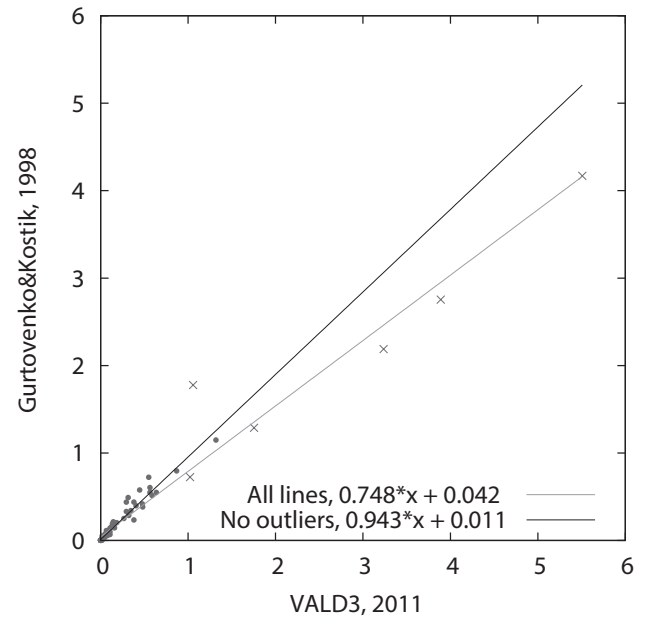


Fig. 3: Oscillator strengths estimated by Gurtovenko & Kostik [5] versus those obtained from VALD [6]. Crosses marks show outliers for absorption lines with significantly different gf values.