

Determination of atomic abundances of solar-type stars

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We discuss the results of abundance determinations of the solar-type stars HD 1835 and HD 10700 using our new procedure. This procedure has the advantage of automated pipeline usage for large amounts of spectroscopic data, with minimal user input. It is based on the spectral synthesis method, where the best values are found with our own developed minimization technique. We reduce the number of free parameters in minimization space using the fit to the observed atomic iron lines. We calibrated our procedure using fits to the observed solar spectrum. Then we determined abundances in two solar-type stars, namely the metal-deficient star HD 10700 and the metal-rich star HD 1835. We found good agreement with previously published results. Thus, we aim to use this procedure for the abundance determination of solar-type stars, particularly planet hosting stars, where the knowledge of abundances is crucial for our understanding of their evolution and formation processes.

Key words: stars: abundances; methods: numerical; methods: data analysis

INTRODUCTION

One of the main reasons for the growing interest to the composition of solar-type stars is that the atmospheric abundance of planet-hosting stars is an important factor that affects the processes of formation and evolution of planetary systems.

Reliable sets of physical parameters of the stellar atmosphere are needed to get accurate abundances from spectral synthesis fitting: effective temperature, surface gravity, microturbulent velocity, rotational velocity and atomic abundances (see [3, 4]).

THE METHOD OF CALCULATIONS

Our procedure is based on the spectra synthesis method. In the current investigation we used 1D homogeneous steady-state plane-parallel LTE models with mixing length approach accounting for convection. We synthesized spectra in the wavelength range 4000 – 9000 Å with a step of 0.025 Å.

The realisation of the paradigm is a computer code, developed for the purpose of pipe-line usage for the determination of abundances in the atmospheres of solar-type stars. The method consists of three following iterations:

I. Robust determination of $\log N(\text{Fe})^1$ in the atmosphere of the observed star, with other parameters being fixed. Namely, microturbulent velocity ξ_t ,

effective temperature T_{eff} , surface gravity $\log g$ and other atomic abundances $\log N(X)$ are fixed to their “initial guess” user defined values. Rotational velocity $v \sin i$ is determined together with $\log N(\text{Fe})$ by our minimization procedure based on fits to the Fe I and Fe II lines.

II. Determination of microturbulent velocity. We compute a two-dimensional synthetic spectral grid $\{\log N(\text{Fe}), \xi_t\}$. $\log N(\text{Fe})$ nodes are clustered around our first-iteration value. Again, minimization is carried out based on fits to the selected Fe I and Fe II features.

III. Determination of atomic abundances for 7 elements, namely: Si, Ca, Ti, V, Cr, Fe, Ni. All atmosphere parameters are fixed to their obtained values. A 1D synthetic spectra grid is computed for different $\log N(X)$ values for each atom. All other parameters are fixed. Again, minimization is carried out based on fits to the selected atomic lines.

On each iteration we recompute the model atmosphere and synthetic spectra for current values of the parameters. This provides a fast convergence in the framework of self-consistency and makes possible the subsequent reduction of “free” parameters. At last, only one non-fixed parameter is left, which is the required atomic abundance itself.

All calculations were carried out with our own

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¹Here $N(\text{Fe})$ is the relative amount of Fe atoms as referred to the total atomic amount: $N(X) = \text{number density of X atoms} / \text{total number density} = n(\text{Fe}) / n_{\text{tot}}$, $n_{\text{tot}} = \sum_X n(X)$. In this frame $N(\text{H}) \approx 0.9$ and the sum of all relative amounts are equal to unity: $\sum_X N(X) = 1$ [2].

software: SAM12 for atmospheric modelling, WITA6 for spectra synthesis, FITA2 for the minimization [4, 8, 9, 11].

Line-lists for the 7 neutral atoms listed above, along with Ti II and Fe II were compiled. For this purpose we used the Vienna Atomic Lines Database VALD 2 [7]. For each atom we synthesized its absorption spectra in the solar atmosphere. We then selected spectral features with central residual fluxes of $r_c < 0.8$. From this set we excluded those severely affected with strong nearby blends. We further accounted for blends by choosing a specific wavelength range for each line, where it fits well the observed solar spectrum [6]. Finally, we used the selected list of wavelength ranges to calculate minimization parameters (see below) to get abundances. Those features that provide incorrect solar abundances were excluded from the list also. After several such iterations we composed reliable lists of atomic features together with corresponding wavelength ranges for 9 ions. We used [2] as a reference for our abundance measurements. We note that more elements could be added into the analysis as soon as more robust atomic data is provided.

We introduce the following minimization parameter:

$$S = \sum_{\nu} (1 - r_{\nu}^s / r_{\nu}^o)^2 / N, \quad (1)$$

so the minimum $S_{\min} = \min_{1..N}\{S\}$ determines the best solution for any given line from the preselected set. Here N is the total dimension of the synthetic spectra grid, r_{ν}^o & r_{ν}^s are the normalized fluxes in the observed and computed spectra, respectively. ν runs through the narrow specified wavelength range across the features core. We adjusted 0.05 dex for the abundance step and set $N = 30$ in the current investigation. For each line from the list, S is calculated and its minimum is found for a certain abundance. Treating this sample as a set of independent measurements of the respective atomic abundance, we formally introduced mean standard deviation:

$$\sigma_X = \sqrt{\frac{\sum_i (\bar{X} - X^i)^2}{N_l(N_l - 1)}}, \quad (2)$$

where $X = \log N(X)$, N_l is a number of lines in the list. We also introduced standard deviation σ_0 for S_{\min} parameter:

$$\sigma_0 = \sqrt{\frac{\sum_j (S_{\min} - S_{\min}^j)^2}{N_l(N_l - 1)}}, \quad (3)$$

where S_{\min}^j is a minimization parameter calculated for j line for the grid node $\{\xi_t^*, \log N(\text{Fe})^*\}$, which refers to S minimum. N_l is a number of lines in the list. Furthermore, the required abundances were

averaged within this $1\text{-}\sigma_0$ range with an inverse variance weighting scheme:

$$\overline{\log N(\bar{X})} = \sum (\log N_i(X) / \sigma_i) / \sum (1 / \sigma_i), \quad (4)$$

where i runs through those values, which placed S into $S_{\min} \pm \sigma_0$ range. Such weighting was done for other determined parameters as well.

RESULTS AND CONCLUSIONS

We have developed a procedure for finding atomic abundances in solar-type atmospheres within a frame of a self-consistent approach. We developed this procedure into a computer code, easily operated by a user with various shell-scripts. We built atomic line-lists and complementary lists of specific wavelength ranges for 9 ions that provide a robust abundance determination for the observed solar spectrum. Table 1 represents the numbers of these carefully selected lines for each ion.

Fe I and Fe II lines were used to determine the solar atmosphere parameters. Two panels in Figure 1 show clear minima of the minimization parameter in two-dimensional parameter space. When carrying out the minimization with Fe II lines, the minimum is less pronounced, but still noticeable. The plots present the results from the second iteration, and we can find that the final result does not differ much from this one.

We measured the abundances of two solar-type stars: the metal-deficient star HD 10700 and the metal-rich star HD 1835. The spectra were obtained with the Fibre-fed Extended Range Optical Spectrograph (FEROS) mounted on the MPG/ESO – 2.2m telescope on the La Silla site in Chile [3]. S/N ratios of ~ 200 were achieved over most of the optical domain at the operating resolution of FEROS ($R \sim 46000$), which is more than sufficient for accurate stellar abundance work. The results presented in Table 2 are consistent with previous investigations (see e.g. [1, 2, 12]).

Thus, we claim that the developed procedure and computer code allow us to determine atomic abundances, microturbulent velocities and rotational velocities in stellar atmospheres in the framework of a self consistent approach. Furthermore, we find our solution to be comparatively stable in respect to the small variations of the main input parameters: T_{eff} , $\log g$ and $\log N(\text{Fe})$ [10]. This developed computer code will be involved in the processing of considerable data sets of solar-type stellar spectroscopic observations e.g. [5].

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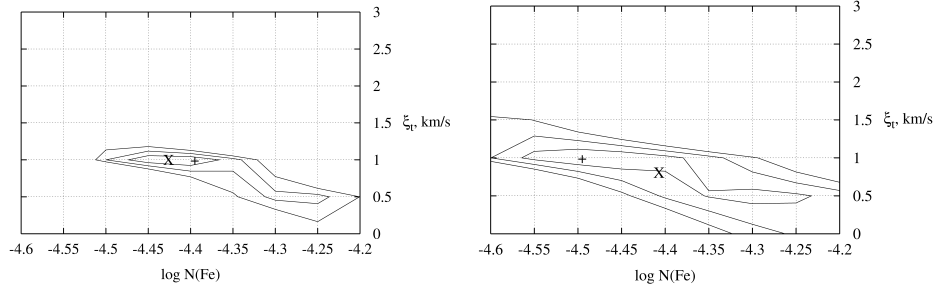


Fig. 1: Minimization parameter S as a function of iron abundance and microturbulent velocity in the atmosphere of the Sun. Left panel refers to Fe I line-list. Right panel refers to Fe II line-list. We show 1-, 2-, 3- σ levels as contour plots. The positions of S_{min} is marked with + and its σ_0 -averaged position is marked with X (see equation 4). The following values correspond to σ_0 -averaged values: $\log N(\text{Fe}) = 4.426 \pm 0.025$ dex, $\xi_t = 1.0$ km/s for Fe I lines, left panel; $\log N(\text{Fe}) = 4.407 \pm 0.041$ dex, $\xi_t = 0.8$ km/s for Fe II lines, right panel. Ranges of iron abundance and microturbulent velocity on the plots are those 2D synthetic spectra grid was computed for. There were 9×7 nodes in $\{\log N(\text{Fe}), \xi_t\}$ parameter space on the second iteration.

Table 1: Number of lines in the composed atomic line-lists.

element	Si I	Ca I	Ti I	Ti II	V I	Cr I	Fe I	Fe II	Ni I
N_l	4	16	30	27	54	54	132	24	52

Table 2: Abundances for HD 10700, the Sun and HD 1835. $\log N(X)$ in dex, mean values correspond to formula 4, errors are one- σ errors (see formula 2). The first column labels the atomic ion.

	HD 10700	The Sun	HD 1835
Ca I	-6.018 ± 0.018	-5.48 ± 0.03	-5.39 ± 0.03
Cr I	-6.975 ± 0.010	-6.303 ± 0.016	-6.098 ± 0.022
Fe I	-5.065 ± 0.009	-4.414 ± 0.010	-4.237 ± 0.010
Fe II	-5.123 ± 0.023	-4.41 ± 0.05	-4.23 ± 0.04
Ni I	-6.363 ± 0.014	-5.753 ± 0.012	-5.608 ± 0.012
Si I	-4.705 ± 0.025	-4.30 ± 0.05	-4.21 ± 0.05
Ti I	-7.498 ± 0.025	-7.102 ± 0.029	-6.90 ± 0.04
Ti II	-7.448 ± 0.025	-7.080 ± 0.027	-6.83 ± 0.05
V I	-8.23 ± 0.08	-7.88 ± 0.11	-7.81 ± 0.17

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