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Calibration approach in the light of Gaia space mission

MARCS model based analysis of δ Eri

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ABSTRACT

Context. We investigate the possibility of using two spectral regions as independent and self-confirming information source for the derivation of fundamental parameters of the δ Eri star. It is also known that different stellar atmosphere models can introduce noticeable systematic effects in abundance derivation, so prior to the core analysis we have corrected a line list that was used in further analysis.
Aims. Compiling a list of atomic lines with calibrated oscillator strengths for cool stellar models to be used in future analysis of Gaia late-type stars. Judgement of the possible usage of optical region vs. infra-red in terms of deriving the information about fundamental stellar parameters and individual abundances of some chemical elements.
Methods. In order to minimize possible modelling effects we have calibrated gf values of the spectral lines used in our analysis against the solar spectrum. For this purpose Spectroscopy Made Easy (SME) package along with MARCS model was utilized. The spectral synthesis method is underlying all our analysis process and calculations done under LTE assumption.
Results. It was found that that the results derived in the optical region of the spectrum fully confirm those, derived in the infra-red in spite of large quality difference between these regions. We also estimated the importance of the error in the initial parameters of the investigated object and their influence on the final result so it allowed us to conclude how accurately we can derive fundamental parameters and, particularly, abundances if the main tool for that is SME.

Key words. methods: data analysis – techniques: spectroscopic – stars: abundances

1. Introduction

This work is done in the framework of the Gaia space mission. Gaia is a cornerstone mission of the ESA Space Program, scheduled for launch in 2012. This ambitious astrometric mission has been designed to enhance our understanding of the formation and evolution of the Milky Way Galaxy. Gaia is a scanning satellite that will repeatedly survey the whole sky to obtain positions, parallaxes and proper motions to μas precision for 10^9 objects brighter than $G \approx 20$ mag ($V \approx$ 20-22). Gaia will feature two additional instruments on board: a spectrophotometric instrument consisting of a blue photometer (BP, covering 330–680 nm) and a red photometer (RP, covering 640–1050 nm) and a medium-resolution spectrograph (Radial Velocity Spectrograph, RVS) covering 847–874 nm which contains the Ca II IR triplet lines (hereafter CaT) and lines of several other chemical elements. These will enable the accurate measurement of radial velocities (RVs) as well as the determination of astrophysical parameters (APs) – $T_{\rm eff}$, $\log g$, [M/H], extinction – (down to $V \approx 16$) and the classification of all the targets (down to $G \approx 20$). For more information about the Gaia mission, see `http://sci.esa.int/gaia/`.

The stellar characterization to be performed by Gaia in terms of $T_{\rm eff}$, $\log g$ and [M/H] will allow population studies for statistically significant numbers of galactic stars. It is also crucial for the processing of Gaia data themselves, because each type of star will receive a dedicated treatment (e.g. templates and masks used for radial velocity determination have to correspond to the nature of the object under study). Since this classification work concerns more than a billion objects, an important effort is presently committed to the development of software that will allow the automatic characterization of stars based on Gaia data. The common approach to carry out these determinations is to match the observed data with synthetic spectra, at low (BPRP) and higher spectral resolution (RVS). Different algorithms are presently explored, such as the use of supervised learning methods (e.g. support vector machines, artificial neural network, nearest neighbours, or k-nearest neighbour) or the application of matrix-inversion techniques (e.g. the MATISSE algorithm, (Recio-Blanco et al. 2006)). The AP determination is thus entirely based on model spectra, and so the results of the AP determination algorithms have to be calibrated to account for deficiencies in the physics of the models used.

The basis for this calibration is formed by a set of benchmark stars. These are well-known, relatively bright stars for which we are compiling amd obtaining, when necessary, a variety of high-quality observations (spectrophotometry, low- and high-resolution spectroscopy, interferometry). In addition, we are compiling or determining fundamental atmospheric parameters ($T_{\rm eff}$, $\log g$, [M/H]) for these stars. As the vast majority of stars observed by Gaia will be of late spectral type, the following selection criteria were applied: 4000 K $\lesssim T_{\rm eff} \lesssim$ 6500 K; dwarfs, subgiants and red giants; solar and sub-solar metallicities. For detailed information on the benchmark star sample, see U. Heiter et al. (2009).

Each of these stars will undergo a series of model tests, i.e. a comparison of synthetic observables – generated from atmospheric models using different assumptions for the input physics – with the observed data. One line of tests, which we call "abundance tests", consists in determining abundances for chemical elements from high-resolution spectra.

Within the context of Gaia, Fe and Ca are the most relevant elements. Different modelling assumptions will result in different abundance values, and the size of the differences will tell us the importance of each assumption for the abundance analysis procedure. In this process we will also obtain possible corrections for metallicity determinations based on a certain model.

The following types of modelling will be included in the abundance tests:

A0: 1D-LTE atmospheric models, LTE line formation, standard set of spectral lines in the optical region, line data from the VALD database[1] (Kupka et al. 1999).
A1: 1D-LTE atmospheric models, **non-LTE line formation**, otherwise same at A0.
A2: **3D-LTE atmospheric models**, LTE line formation, otherwise same at A0.
A3: **3D-LTE atmospheric models, non-LTE line formation**, otherwise same at A0.
A4: 1D-LTE atmospheric models, LTE line formation, **line data** from different sources.
A5: 1D-LTE atmospheric models, LTE line formation, **non-standard set of spectral lines**, e.g. lines in the RVS spectral region.

In this paper, we report a first application of this scheme: an abundance test of type A5 vs. A0, for the benchmark star δ Eri (HD 23249, HR 1136, HIP 17378, V=3.51$\pm$0.02). In particular, we compare abundances derived from two different sets of lines in two different wavelength regions. An example for another A5-type test in the literature for the same star can be found in Affer et al. (2005), who used different sets of spectral lines selected based on excitation energy. To the best of our knowledge, this is the first study of δ Eri focussing on the RVS spectral region.

In Sect. 2 we discuss the fundamental parameters of δ Eri. In Sect. 3 we describe the observations and mention some aspects of the data reduction. In Sect. 4 we focus on the preparation of the line list in terms of *gf* calibrations using the Kurucz solar spectrum and a MARCS solar model. In Sect. 5 we present the analysis procedure and our results for δ Eri, and Sect. 6 completes the paper with conclusions regarding this work.

2. Fundamental parameters of δ Eri

δ Eri is a K-type subgiant with solar metallicity. Thévenin et al. (2005) determined the limb-darkened angular diameter of δ Eri from VLTI/VINCI interferometry to be $\Theta = 2.39 \pm 0.03$ mas. Together with the bolometric flux, $F_{\rm bol}$, the angular diameter can be used to derive a fundamental value for the effective temperature. $F_{\rm bol}$ can be determined in two ways – either from the V magnitude and the bolometric correction $\rm BC_V$, or from an integration over spectrophotometry and narrow- or broadband photometry covering the whole wavelength range in which the stellar flux is emitted. For the former approach, the calibration of Alonso et al. (1999) gives $\rm BC_V = -0.24 \pm 0.05$ for δ Eri, which results in $F_{\rm bol} = 1.26 \cdot 10^{-9}$ W m^{-2} with an error of 5%. This gives $T_{\rm eff} = 5070 \pm 70$ K, where the error in $T_{\rm eff}$ is obtained by propagating the errors in $BC_{\rm V}$ and Θ.

In a second approach, we estimated $F_{\rm bol}$ from the spectrophotometry by Alekseeva et al. (1997) in the range 320 to 735 nm, supplemented in the IR by the four red-most bands of

[1] http://vald.astro.univie.ac.at

the 13-color photometry by Johnson & Mitchell (1975) and the three 2MASS (Skrutskie et al. 2006) bands (J, H, K_s) with the absolute flux calibration by Cohen et al. (2003). The integration over these data gives $F_{\rm bol} = 1.04^{+0.2}_{-0.1} \cdot 10^{-9}$ W m^{-2}, which corresponds to $T_{\rm eff}$= 4840^{+230}_{-120} K. The bolometric flux may be underestimated by as much as 20% due to unknown photometry outside the observed wavelength range. On the other hand, $F_{\rm bol}$ may be overestimated due to spectral features not being represented correctly by the observed photometry. Thus, the more direct approach turns out to give a less accurate temperature estimation.

Table 1 summarizes these $T_{\rm eff}$ values together with a compilation of atmospheric parameter determinations found in the literature after the year 2000[2], including also metallicity [M/H] and microturbulence ξ. In Section 5, we carry out a spectroscopic analysis with our own data and models, using the following starting values for the stellar parameters: $T_{\rm eff}$=5070 K, $\log g$=3.78, ξ=1.08 kms^{-1}.

Table 1. Compilation of atmospheric parameter determinations for δ Eri found in the literature. The column labelled "Method for $T_{\rm eff}$, $\log g$" indicates the methods for $T_{\rm eff}$ and $\log g$ determination used by the authors. *Spectroscopy* refers to excitation and ionization equilibrium for $T_{\rm eff}$ and $\log g$, respectively, in a spectroscopic analysis of high-resolution spectra. *IRFM* refers to the infrared flux method *Parallax* means a gravity determination using the Hipparcos parallax, $T_{\rm eff}$ and a mass estimate from stellar isochrones.

$T_{\rm eff}$ [K]	$\log g$ [cgs]	[M/H]	ξ [km s^{-1}]	Reference	Method for $T_{\rm eff}$; $\log g$
5070 ± 70				this paper	Θ+$F_{\rm bol}$ from $BC_{\rm V}$
4840^{+230}_{-120}				this paper	Θ+$F_{\rm bol}$ from spectrophotometry
5020 ± 70	3.73 ± 0.1	0.24 ± 0.14	0.80	Bensby et al. (2003)	spectroscopy; parallax
5023 ± 419	4.14 ± 0.18	0.18 ± 0.07	1.04	Allende Prieto et al. (2004)	IRFM; parallax
5074 ± 60	3.77 ± 0.16	0.13 ± 0.08	1.08 ± 0.06	Santos et al. (2004)	both spectroscopy
5140 ± 105	4.10 ± 0.26	0.05 ± 0.13	1.32 ± 0.18	Affer et al. (2005)	both spectroscopy (their "Method 1")
5100 ± 100	3.8 ± 0.10	0.18 ± 0.09	0.60	Luck & Heiter (2005)	both spectroscopy
5095 ± 44	3.98 ± 0.06	0.16 ± 0.03	0.85	Valenti & Fischer (2005)	synthetic spectrum fit
5008	3.78 ± 0.05	0.21 ± 0.11	0.88	Ramírez et al. (2007)	IRFM; parallax
5044 ± 80	3.84 ± 0.10	0.12 ± 0.07	0.92 ± 0.20	Fuhrmann (2008)	spectroscopy (Balmer line wings; and Mg Ib line wings)
5150 ± 51	3.89 ± 0.08	0.13 ± 0.04	1.01 ± 0.06	Sousa et al. (2008)	both spectroscopy (extended line list compared to Santos et al. 2004)

3. Observations and some notes on data reduction

Spectra for δ Eri were obtained using the SARG spectrograph (Gratton et al. 1997) mounted on the Italian TNG at La Palma, Spain, in a service-mode observing run in 2008 (PI Heiter). Given the brightness of the target (and additional abudance tests planned), the highest resolving power achievable (R = 164 000) was chosen. Using two different grisms, spectra with nominal wavelength coverage of 3600 − 5140 Å and red 4960 − 10110 Å, re-

[2] see the PASTEL database at `http://pastel.obs.u-bordeaux1.fr/`

widthGwidthG

Fig. 1. The upper panel shows a fragment of δ Eri spectrum obtained in the optical region and the lower one shows spectrum in the IR with the two Ca II lines (8498 Åand 8542.1 Årespectively).

spectively, were obtained. The exposure times were adjusted to reach a signal-to-noise ratio (S/N) of order 400. Table 3 gives a brief overview of the observations.

Table 2. Observations of δ Eri.

date S/N$_{\rm exp}$	target	Mode	$t_{\rm exp}$ [s]
2007/09/01 ?	δ Eri	Red	260
2007/09/01 ?	δ Eri	Blue	650

Data reduction was performed using REDUCE (Piskunov & Valenti 2002). REDUCE uses a cluster-analysis method for order tracing. This is best done on a flat-field spectrum as it has no absorption lines and high signal. REDUCE determines cluster groups according to a signal-level criterion and fits them with third-order polynomials. In contrast to many other data-reduction packages, no assumption is made about the cross-dispersion profile: it is recovered from the observations. To check the true quality of our data, we estimated the signal-to-noise (S/N) ratio in the centre of each order for the spectral regions of interest. The resulting S/N values are somewhat lower than expected. For the optical region of interest here (see below), the S/N is found to be in the $200-400$ range, but in the IR it only reaches 70-90. On top of that, the resolving power is not as high as claimed and degrades towards the red, as measured on arc-lamp calibration frames. In order 110 ($\lambda_c = 5550$ Å) we found $R = 120\,000 - 130\,000$ decreasing to $R = 85\,000 - 90\,000$ in order 66 ($\lambda_c = 9280$ Å). Consulting the TNG staff, we learned that the spectrograph was slightly defocused during the time of observation. Fringing further limits the S/N of the near-IR data. We nonetheless deem the data quality to be sufficient for our scientific goals.

Various attempts were made to deal with the near-IR fringing in a satisfactory way. The use of a telluric standard star of early spectral type observed during the same night proved difficult, as its spectrum contain strong Paschen lines in the Gaia-RVS spectral region. In the end, the best results were obtained by standard flat-field division. On Fig. 1 you can see a small fragments of δ Eri spectra in optical and IR regions.

4. Preparation of the line list

A large effort was put on the preparation and selection of suitable spectral lines, both in the optical and in the RVS spectral regions. In the optical, we selected the wavelength region between 555 and 675 nm. This is a region widely used in the literature for late-type stars as it is optimal in terms of line density (a large number of lines, not too dense and hence unblended, are available). The line list in the optical region compiled here represents our "standard set of spectral lines" mentioned above and is to be applied to the full set

Fig. 2. The $\log gf$ corrections for the optical wavelength region as a function of calculated equivalent width. Rhomb symbols are the corrections for Fe I lines and triangles show corrections for Ca I.

of benchmark stars with minor adaptations for earlier spectral types. The selection of the spectral lines was performed on the basis of line data extracted from the VALD[3] (Kupka et al. 1999) and the Kurucz solar spectrum (Kurucz 2005). We excluded those spectral lines which were blended according to the criterion formulated as follows:

$$\frac{R_{cen}^{blend}}{R_{cen}^{line}} \geq 0.2 \qquad (1)$$

R_{cen} here is the central depth of the spectral line returned in the VALD line list. We compare this value for the blend to the value of the main component that contributes to the spectral feature. Thus, all lines for which this ratio was about 20% or less we counted as appropriate for the analysis.

This line list was calibrated in terms of oscillator strengths $\log gf$ against the solar spectrum, using a MARCS solar model (Gustafsson et al. 2008) with the help of the SME package (Valenti & Piskunov 1996; Valenti & Fischer 2005). Note that we also used MARCS models in the analysis of δ Eri, ensuring consistency of the calibration procedure of oscillator strengths and the abundance analysis. All calculations are made under LTE assumption. The chemical elements of interest are Ca and Fe and line selection and $\log gf$ calibrations were performed only for spectral lines of these species. All line data apart from $\log gf$ are from the VALD database.

For the synthesis calculation we used the solar abundances from Asplund et al. (2005), $\log \epsilon$(Ca)=6.31 and $\log \epsilon$(Fe)=7.45, and the following solar parameters: $T_{\rm eff}$= 5777 K, $\log g$= 4.44, ξ = 1.0 km s^{-1}, ζ = 2.8 km s^{-1}, where ξ and ζ are the micro- and macroturbulence parameters, respectively. For the analysis of δ Eri, we had to exclude a few spectral lines from the solar-calibrated line list. Due to the lower temperature of δ Eri compared to the Sun, the number and strength of spectral lines increases, leading to more blends. The final line lists contain 10 Ca I and 109 Fe I lines in the optical wavelength region, which can be found in Tables 3 and 4, respectively.

In Fig. 2 $\log gf$ corrections derived from the solar spectrum for lines in the optical wavelength region adopted for the δ Eri analysis are dsiplayed. From the plot it can be clearly seen that the corrections we had to apply for the particular solar parameters and abundances are mainly positive, with a mean correction of +0.11±0.16 dex for Fe I and +0.05±0.05 dex for Ca I. The goodness of the fit was estimated for every line by calculating the standard deviation of the synthetic spectrum fit to the solar observation (σinTables3and4).EvenforthethreeFe Ilines,whichshowthelargestrequiredcorrectionof$\log gf$ (≳0.4 dex), the standard deviation values lie in range from 0.019 to 0.035, which is comparable to the average of the σvaluesforallopticalFe Ilines(0.023).Inotherwords,wemayconcludethatevenfortheseseeminglylargecorrectionswewereablet

[3] http://vald.astro.univie.ac.at

Fig. 3. The fit of the theoretical line profile (green line) after applied $\log gf$ correction to the solar Fe I spectral line (black line).

Table 3. Resulting $\log gf$ corrections for Ca I lines that were used in the spectral analysis of δ Eri.

Wavelength, Å	Ei, eV	$\log gf_{\rm MARCS}$	$\log gf_{\rm MARCS} - \log gf_{\rm VALD}$	STD	$log\gamma_6$
5588.7490	2.526	0.011	0.358	0.076	−7.628
5857.4512	2.933	0.048	0.240	0.055	−7.316
5867.5620	2.933	−0.003	−1.570	0.033	−7.460
6162.1729	1.899	−0.057	−0.090	0.082	−7.189
6166.4390	2.521	0.051	−1.142	0.013	−7.264
6449.8081	2.521	0.091	−0.502	0.052	−7.652
6455.5981	2.523	0.032	−1.340	0.024	−7.652
6471.6621	2.526	0.100	−0.686	0.027	−7.704
6493.7808	2.521	0.074	−0.109	0.063	−7.704
6499.6499	2.523	0.122	−0.818	0.011	−7.704

Table 4. Resulting $\log gf$ corrections for Fe I lines that were used in the spectral analysis of δ Eri.

Wavelength, Å	Ei, eV	$\log gf_{\rm MARCS}$	$\log gf_{\rm MARCS} - \log gf_{\rm VALD}$	STD	$log\gamma_6$
8514.0723	2.198	−2.362	-0.218	0.002	−7.361
8515.1084	3.018	−2.035	-0.161	0.001	−7.322
8526.6689	4.913	−0.613	-0.095	0.001	−6.977
8571.8037	5.010	−1.061	-0.030	0.034	−7.480
8582.2568	2.990	−2.078	-0.227	0.026	−7.780
8592.9512	4.956	−0.792	-0.051	0.001	−6.504
8611.8037	2.845	−2.076	-0.013	0.227	−7.900
8613.9404	4.988	−1.065	-0.043	0.033	−7.470
8616.2803	4.913	−0.881	-0.069	0.018	−7.520
8621.6006	2.949	−2.235	-0.201	0.019	−7.780
8674.7461	2.831	−1.850	-0.213	0.005	−7.371
8688.6260	2.176	−1.208	-0.059	0.016	−7.691

5. Analysis

The analysis of δ Eri is based on the spectral synthesis method. The starting values for the atmospheric parameters are discussed in Section 2. The metallicity of the atmospheric models used for the analysis was set to zero for all calculations. The starting value for the macroturbulence was ζ=0 km s^{-1}.

The main tool we used, SME, is very flexible and allows fitting of many spectral parameters at the same time. Basically it finds an optimal fit to the data by minimizing the χ^2, i.e. minimizing the difference between synthetic spectrum and observed data. This is done by selecting the desired spectral regions and choosing a set of free parameters. The code changes these free parameters and re-calculates the synthesis until convergence is achieved. If the initial parameters are not known well it is better not to set more than two free parameters, in order to avoid correlations between the tuned parameters.

We started with the optical wavelength region, finding the best-fit values for $T_{\rm eff}$ as well as for the turbulent and radial velocities. The latter was set to be free throughout all calculation runs, since it does not correlate with other fundamental parameters. For $\log g$ we relied on a recent determination using the parallax and kept it fixed. Macroscopic line broadening was assumed to be represented by a Gaussian profile parameterized by the macroturbulent velocity only. Thus, the derived value of ζ includes rotational and instrumental broadening. A preliminary synthesis calculation resulted in $T_{\rm eff}$=5026 K, ξ=1 km s^{-1}and ζ=3.5 km s^{-1}. The radial velocity was found to be $v_{\rm rad} = -3.5$ km s^{-1}.

To estimate the effect which can be produced by choosing different initial parameters, we ran SME several times, where the effective temperature was perturbed by $\pm$200 K and individual abundances of Fe and Ca by $\pm$0.2 dex. For a more precise determination of $T_{\rm eff}$ we included four Fe II lines free of blends with $\log gf$ values taken from Meléndez & Barbuy (2009) The derived average $T_{\rm eff}$=5035 $\pm$32 K was used for all further calculations in the optical as well as in the IR (RVS) region.

The final step was to derive the individual abundances of Ca and Fe from fitting the optical and the RVS regions separately. For the optical region, we derive $\log \epsilon$(Fe I)=7.56 $\pm$0.03 dex and $\log \epsilon$(Ca I)=6.37 $\pm$0.03 dex. For the RVS region, we derive $\log \epsilon$(Fe I)=7.57$\pm$0.03 dex and $\log \epsilon$(Ca II)=6.39 $\pm$0.01 dex. Thus, the abundances derived from the two different spectral regions are in good agreement. Relative to the solar abundances used for the line-list calibration (Section 4), our analysis results in [Fe/H]=+0.12 $\pm$0.03 dex and [Ca/H]=+0.07 $\pm$0.03 dex. These values agree with the lower end of the overabundance range ([M/H]= +0.1 ... +0.25) found for δ Eri in previous studies (see Table 1). As a final step, we performed a consistency check by assuming the metallicity of +0.11 dex, which showed no change in the abundances for the optical region and small changes for the abundances in the IR part of the spectrum. The difference for Ca ($Ca_{opt} - Ca_{IR}$) is 0.088 dex and for Fe is 0.224 dex. All results, derived in both regions can be found in Table 6.

Table 6. Summary of the results derived for δ Eri from optical and infra-red spectral regions.

T_{eff}, K	log g	log $\epsilon(Fe)$	log $\epsilon(Ca)$	
5035 $\pm$32	3.78	7.56 $\pm$0.03	6.37 $\pm$0.03	Optical
		7.57 $\pm$0.03	6.39 $\pm$0.01	IR

6. Conclusions

This is the first analysis of a benchmark star in the framework of the Gaia space mission. The focus of this paper is on methodology which must be robust and effective, as it is to be applied to a sizable number of late-type benchmark stars. We shall test this new method on stars that are, e.g., 1000 K cooler than δ Eri. The spectrum of such stars is expected to be much more challenging to analyse due to the problems with continuum normalization and line blending. This will be the subject of future investigations.

For δ Eri, the method works well and gives good mutual confirmation for the individual abundances independently derived from optical and Gaia-RVS spectra, even in LTE. At 0.01 dex, the abundances derived are indistinguishable within the errors and their agreement is rather satisfactory. But this result was achieved based on high-resolution spectra, while Gaia spectra will not be of the same quality.

Keeping all that in mind, our recommendations would be the following: test this methodology against a comprehensive set of benchmark stars (already scheduled for observations). This will show the possible limitations of such a data treatment. If this turns out to be a success, one can start to degrade the data quality to reflect typical Gaia-RVS data. At that stage, problems may become apparent in the form of systematic offsets in inferred quantities and the most direct approach used in high-resolution spectroscopy will no longer be applicable. This may result in the introduction of some correction factors or weights. Finally, one of the future tasks will be implementation of 3D model atmospheres and line-synthesis calculation in NLTE.

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Table 4. Same as Table 3 but for Fe I lines.

Wavelength	Ei	$\log gf_{\mathrm{MARCS}}$	$\log gf_{\mathrm{VALD}} - \log gf_{\mathrm{MARCS}}$	STD	van-der-Waals
5554.8818	4.548	−0.151	−0.289	0.037	−7.125
5560.2070	4.434	−1.025	0.049	0.011	−7.189
5569.6182	3.417	−0.511	0.025	0.001	−7.204
5576.0889	3.430	−0.860	−0.140	0.010	−7.201
5577.0249	5.033	−1.458	0.058	0.020	−7.390
5584.7642	3.573	−2.144	−0.176	0.120	−7.668
5587.5742	4.143	−1.601	−0.249	0.056	−7.800
5607.6641	4.154	−2.177	0.056	0.012	−7.229
5618.6309	4.209	−1.261	0.053	0.019	−7.264
5619.5869	4.386	−1.452	0.060	0.058	−7.233
5624.0220	4.386	−1.118	−0.362	0.054	−7.234
5633.9458	4.991	−0.158	0.052	0.049	−7.337
5635.8218	4.256	−1.551	−0.339	0.028	−7.173
5636.6958	3.640	−2.491	0.059	0.017	−7.581
5638.2622	4.220	−0.731	−0.139	0.007	−7.269
5640.3071	4.638	−1.584	0.210	0.034	−7.310
5651.4692	4.473	−1.745	−0.255	0.004	−7.187
5652.3179	4.260	−1.743	−0.207	0.018	−7.251
5653.8652	4.386	−1.354	−0.286	0.032	−7.242
5655.1758	5.064	−0.455	−0.185	0.063	−7.390
5661.3452	4.284	−1.827	0.091	0.019	−7.244
5662.5161	4.178	−0.352	−0.221	0.001	−7.530
5677.6841	4.103	−2.617	−0.083	0.004	−7.268
5691.4971	4.301	−1.399	−0.121	0.023	−7.259
5696.0889	4.548	−1.858	0.138	0.008	−7.156
5698.0200	3.640	−2.665	−0.015	0.024	−7.550
5704.7329	5.033	−1.189	−0.220	0.016	−7.300
5705.4639	4.301	−1.432	0.077	0.025	−7.260
5712.1309	3.417	−2.003	0.013	0.025	−7.221
5717.8330	4.284	−0.974	−0.156	0.050	−7.248
5730.8540	4.913	−1.806	0.361	0.012	−7.300
5731.7622	4.256	−1.069	−0.231	0.018	−7.271
5732.2949	4.991	−1.394	−0.166	0.039	−7.353
5741.8462	4.256	−1.612	−0.242	0.027	−7.272
5752.0322	4.549	−0.844	−0.333	0.025	−7.510
5753.1211	4.260	−0.690	0.002	0.002	−7.258
5760.3442	3.642	−2.433	−0.057	0.012	−7.549
5775.0811	4.220	−1.040	−0.258	0.036	−7.530
5778.4531	2.588	−3.459	0.029	0.028	−7.576

Table 4. continued.

Wavelength	Ei	$\log gf_{\mathrm{MARCS}}$	$\log gf_{\mathrm{VALD}} - \log gf_{\mathrm{MARCS}}$	STD	van-der-Waals
5784.6572	3.396	−2.543	0.011	0.046	−7.234
5793.9131	4.220	−1.581	−0.119	0.047	−7.278
5804.4629	4.283	−1.866	−0.174	0.049	−7.271
5809.2168	3.883	−1.753	−0.087	0.041	−7.154
5814.8052	4.283	−1.800	−0.170	0.029	−7.272
5835.0981	4.256	−2.097	−0.273	0.015	−7.220
5852.2168	4.548	−1.178	−0.152	0.008	−7.188
5855.0762	4.608	−1.511	0.055	0.018	−7.158
5856.0830	4.294	−1.531	0.051	0.029	−7.532
5859.5859	4.549	−0.459	0.040	0.017	−7.510
5883.8130	3.960	−1.075	0.051	0.005	−7.136
5905.6709	4.652	−0.717	0.047	0.024	−7.144
5929.6670	4.548	−1.173	0.050	0.023	−7.204
5930.1729	4.652	−0.188	0.059	0.007	−7.149
5976.7769	3.943	−1.125	−0.118	0.044	−7.540
5983.6802	4.549	−0.521	−0.947	0.025	−7.510
6003.0098	3.881	−0.965	−0.155	0.015	−7.181
6007.9600	4.652	−0.603	0.006	0.043	−7.510
6008.5562	3.884	−0.708	−0.278	0.022	−7.540
6012.2378	2.223	−3.900	−0.138	0.103	−7.649
6024.0791	4.548	0.046	−0.166	0.036	−7.225
6027.0508	4.076	−1.073	−0.016	0.073	−7.780
6078.4912	4.796	−0.134	0.046	0.043	−7.420
6078.9990	4.652	−0.961	0.043	0.022	−7.177
6082.7080	2.223	−3.539	0.049	0.015	−7.654
6093.6431	4.607	−1.315	−0.185	0.021	−7.202
6094.3638	4.652	−1.552	−0.388	0.019	−7.179
6127.9058	4.143	−1.351	−0.048	0.036	−7.790
6136.6152	2.453	−1.393	−0.007	0.007	−7.609
6136.9932	2.198	−2.916	−0.034	0.018	−7.691
6151.6172	2.176	−3.273	0.039	0.011	−7.696
6173.3340	2.223	−2.833	0.027	0.027	−7.690
6187.9868	3.943	−1.626	0.043	0.032	−7.179
6200.3130	2.608	−2.341	0.025	0.026	−7.589
6213.4292	2.223	−2.515	0.027	0.016	−7.691
6220.7759	3.881	−2.314	−0.146	0.025	−7.208
6226.7300	3.883	−2.074	−0.146	0.022	−7.208
6240.3101	4.143	−2.180	0.097	0.024	−7.790
6240.6450	2.223	−3.260	0.039	0.020	−7.661

Table 4. continued.

Wavelength	Ei	$\log gf_{\rm MARCS}$	$\log gf_{\rm VALD} - \log gf_{\rm MARCS}$	STD	van-der-Waals
6246.3169	3.602	−0.761	0.064	0.001	−7.221
6252.5542	2.404	−1.658	−0.029	0.011	−7.621
6265.1309	5.033	−2.497	1.565	0.020	−7.320
6270.2222	2.858	−2.553	0.089	0.022	−7.591
6271.2759	3.332	−2.725	0.022	0.020	−7.278
6297.7920	2.223	−2.693	−0.047	0.021	−7.694
6301.5000	3.654	−0.466	−0.252	0.011	−7.540
6302.4941	3.686	−1.050	0.077	0.025	−7.540
6330.8379	4.733	−1.154	−0.586	0.017	−7.179
6335.3281	2.198	−2.232	0.055	0.008	−7.698
6336.8232	3.686	−0.837	−0.019	0.003	−7.207
6338.8760	4.795	−0.899	−0.161	0.021	−7.148
6380.7432	4.186	−1.203	−0.021	0.002	−7.790
6385.7158	4.733	−1.799	−0.111	0.007	−7.187
6392.5381	2.279	−3.944	−0.086	0.003	−7.643
6393.6001	2.433	−1.495	0.063	0.008	−7.622
6408.0181	3.686	−0.805	−0.213	0.014	−7.540
6411.6470	3.654	−0.600	0.005	0.009	−7.221
6419.9419	4.733	−0.248	0.008	0.005	−7.193
6430.8442	2.176	−1.994	−0.012	0.001	−7.704
6481.8691	2.279	−2.897	0.019	0.021	−7.646
6494.9800	2.404	−1.255	−0.018	0.001	−7.629
6496.4658	4.795	−0.527	0.039	0.004	−7.175
6653.8501	4.154	−2.387	0.046	0.012	−7.153
6703.5659	2.758	−2.997	0.041	0.029	−7.633
6710.3159	1.485	−4.794	0.047	0.022	−7.733
6713.7432	4.795	−1.396	−0.204	0.012	−7.207
6725.3530	4.103	−2.185	−0.115	0.005	−7.181
6726.6660	4.607	−0.989	0.033	0.033	−7.520
6733.1499	4.638	−1.406	0.044	0.016	−7.247
6739.5200	1.557	−4.872	0.048	0.012	−7.726