The accuracy of stellar atmospheric parameter determinations: a case study with HD 32115 and HD 37594

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ABSTRACT

We present detailed parameter determinations of two chemically normal late A-type stars, HD 32115 and HD 37594, to uncover the reasons behind large discrepancies between two previous analyses of these stars performed with a semi-automatic procedure and a “classical” analysis. Our study is based on high resolution, high signal-to-noise spectra obtained at the McDonald Observatory. Our method is based on the simultaneous use of all available observables: multicolor photometry, pressure-sensitive magnesium lines, metallic lines and Balmer line profiles. Our final set of fundamental parameters fits, within the error bars, all available observables. It differs from the published results obtained with a semi-automatic procedure. A direct comparison between our new observational material and the spectra previously used by other authors shows that the quality of the data is not the origin of the discrepancies. As the two stars require a substantial macroturbulence velocity to fit the line profiles, we concluded that neglecting this additional broadening in the semi-automatic analysis is one origin of discrepancy. The use of Fe i excitation equilibrium and of the Fe ionisation equilibrium, to derive effective temperature and surface gravity, respectively, neglecting all other indicators leads to a systematically erroneously high $T_{\text{eff}}$. We deduce that the results obtained using only one parameter indicator might be biased and that those results need to be cautiously taken when performing further detailed analyses, such as modelling of the asteroseismic frequencies or characterising transiting exoplanets.

Key words: techniques: spectroscopic – stars: fundamental parameters – stars: individual: HD 32115, HD 37594, HD 49933

1 INTRODUCTION

The advent of space missions aiming to obtain very accurate photometry for an increasing number of stars (e.g. CoRoT and Kepler) led to the necessity of a large scale work to obtain high precision spectroscopic fundamental parameters, effective temperature in particular, to allow i.e. the modelling of the pulsation frequencies or the characterisation of transiting exoplanets. This large spectroscopic analysis campaign can be performed within reasonable time-scales only with automatic and semi-automatic procedures. It is therefore crucial to critically compare some of the results obtained in this way with other independent, more “classical”, methods and highlight the discrepancies to understand their origin and improve these procedures.

Bruntt et al. (2010) derived fundamental parameters for a set of 23 solar-type stars adopting various different techniques (e.g. asteroseismology, parallax, spectroscopy), concluding that purely spectroscopic methods lead to results comparable to the more robust ones, although small corrections might be necessary. It is important to carefully assess whether there are cases where the spectroscopy fails in recovering the correct set of parameters, and if such erroneous parameters are produced, we need to understand why and correct the methodology.

In this work we concentrate on a few discordant results obtained with the semi-automatic procedure developed by H. Bruntt (see e.g. Bruntt et al. 2002) and adopted by many authors to analyse several different types of stars.

For the solar-type pulsator HD 49933, Gillon & Magain...
latter was affected by a spectrograph defect, preventing the normalisation. We were able to perform a reliable normalisation of the Hy line using the artificial flat-fielding technique described by Barklem et al. (2002). This normalisation procedure was already successfully applied to data obtained with this spectrograph by Kolenberg et al. (2010).

2.1 Comparing spectrographs

As mentioned in Sect. 1, Bruntt (2009) left open the possibility that the discrepancies obtained for HD 49933 with their previous results (B08) were caused by systematic differences in the observed spectra (Bruntt 2009, analysed HARPS spectra, while B08 analysed CORALIE spectra, where both instruments operate at La Silla, but on different telescopes). We checked if this is the case. This control is important, to remove the observed spectra as a possible source of systematic uncertainties and also to check the quality of the normalisation, as independently performed on spectra obtained with different instruments.

Here we compare the spectra obtained with TS and CORALIE (used by B08), which is an échelle spectrograph, reaching a resolution of R ∼ 50,000, mounted on the 1.2-m Euler telescope in La Silla, Chile. Details of the CORALIE spectrograph and on the data reduction can be found in De Cat et al. (2006).

Figure 1 shows a comparison between the TS and the CORALIE spectrum of HD 32115 in the wavelength range around the strong \FeII $λ$5018 Å line. In this plot we display also the difference spectrum (in % shifted upwards of 0.9) between the two spectra.

The rms of the difference spectrum (a portion is shown in Fig. 1), calculated on several continuum regions is comparable to the rms of the CORALIE spectrum. We obtained the same conclusion comparing the TS and CORALIE spectra with the ones used by Bikmaev et al. (2002). The spectra of HD 37594 demonstrate an identical behavior.

These comparisons let us conclude that there are no significant differences between the spectra used in the present work and those employed by Bikmaev et al. (2002) and by B08, thus excluding the quality of the data as the origin of the discrepancies described in
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3 THE FUNDAMENTAL PARAMETERS

We adopted photometric indicators to set the starting point in the determination of the fundamental parameters, which we refined making use of hydrogen lines, metal lines, and, as a final check, synthetic colors and the spectral energy distribution. Spectroscopic tuning of the fundamental parameters is needed because different photometric systems and calibrations give different parameters and uncertainties. Spectroscopic analysis, performed with this way, will produce a parameter set which fits all the indicators consistently, the uncertainties are thus reduced for those derived from photometric analysis alone.

We computed model atmospheres of HD 32115 and HD 37594 using the LLMON atlas stellar model atmosphere code (Shulyak et al. 2004). For all the calculations Local Thermodynamical Equilibrium (LTE) and plane-parallel geometry were assumed. We used the VALD database (Piskunov et al. 1995; Kupka et al. 1999; Ryabchikova et al. 1999) as a source of atomic line parameters for opacity calculations. Convection was implemented according to the Canuto & Mazzitelli (1991, 1992) model of convection (see Sect. 3). In addition, this comparison sets an upper limit of ±1% on the uncertainty due to the normalisation.

3.1 Photometric indicators

Initial guesses for the effective temperature ($T_{\text{eff}}$) and surface gravity (log $g$) were obtained from calibrations of different photometric indices for normal stars. The effective temperature and gravity were derived from Strömgren photometry (Hauck & Mermilliod 1998) with calibrations by Moon & Dworetsky (1985), Napwotzki et al. (1993), Balona (1994), Ribas et al. (1997), Castelli et al. (1997), and from Geneva photometry (Rufenacht 1988) with calibrations by North & Niclot (1994).

Figure 1. Comparison between the spectra of HD 32115 obtained with the CORALIE spectrograph (dashed red line) and the TS spectrograph (thick black line) in the wavelength region around the $\lambda$5018Å Fe ii line. The difference (in %) between the two spectra is shown by the dashed-dotted blue line. The difference spectrum is shifted upwards by 0.9. No difference is visible between the two spectra, except for the core of the strong Fe ii line at $\lambda$5018Å which displays the difference in resolution between the two instruments.

Table 1 summarises the set of $T_{\text{eff}}$ and log $g$ obtained with each adopted calibration and photometry, reflecting the scattering due to the use of different calibrations and photometric systems.

The interstellar reddening plays an important role when converting the observed photometry into fundamental parameters. We calculated the interstellar reddening adopting the galactic extinction maps provided by Amores & Lépine (2005), obtaining E(B-V) = 0.00 for both stars, which we adopt for the determination of the synthetic colors (see Sect. 4.1.1) and spectral energy distribution (see Sect. 4.1.2). This is also in agreement with other models of interstellar extinction in the solar neighborhood, e.g. Lallement et al. (2003).

Excluding the results obtained with the calibration by Castelli et al. (1997), which gives much lower $T_{\text{eff}}$ and log $g$ compared to the others, we set the center for the calculation of our model grid to $T_{\text{eff}} = 7250$ K and log $g = 4.2$, for HD 32115 and to $T_{\text{eff}} = 7100$ K and log $g = 4.2$, for HD 37594, adopting steps of 50 K in $T_{\text{eff}}$ and 0.1 in log $g$.

3.2 Spectroscopic indicators

3.2.1 Hydrogen lines

For a fully consistent abundance analysis, the photometric parameters must be checked and eventually tuned according to spectroscopic indicators, such as hydrogen line profiles. In the temperature range where HD 32115 and HD 37594 lie, the hydrogen line wings are sensitive almost exclusively to $T_{\text{eff}}$ variations. To spectroscopically derive $T_{\text{eff}}$ from hydrogen lines, we fitted synthetic line profiles, calculated with SYNTH3 (Kochukhov 2007), to the observed Hγ profiles. SYNTH3 incorporates the code by Barklem et al. (2000) that takes into account not only self-broadening but also Stark broadening (see their Sect. 3). For the latter, the default mode of SYNTH3, adopted in this work, uses an improved and extended HLINOP routine (Kurucz 1995).

Figure 2 shows a comparison of the observed Hγ line profiles of HD 32115 and HD 37594, with two synthetic profiles for each star. One synthetic profile was calculated with our final set of parameters while the other one with the set of parameters by B08.

For both stars, the synthetic spectrum corresponding to our final model (see Sect. 3.1) does not fit the Hγ profile perfectly, this would require a lower temperature by ∼80–100 K. We attribute most of the difference between our final synthetic and observed Hγ profiles to the normalisation, which is always challenging for hydrogen lines observed with échelle spectra. To quantify the uncertainty introduced by the normalisation, we compared the TS Hγ profile with the one we obtained from the CORALIE spectrum. The maximum difference between the two profiles (independently normalised) is ∼2%, less than the difference introduced in the synthetic spectrum by changing $T_{\text{eff}}$ by 100 K.

Figure 3 shows that the effective temperatures adopted by B08 for the two stars are too high to even remotely fit the hydrogen line profiles.

3.2.2 Gravity from metallic lines with extended wings

The surface gravity was derived from two independent methods based on line profile fitting of Mg i lines with developed wings (analysis described here) and ionisation balance for several elements (analysis performed in Sect. 4.2.3). The first method is described in Fuhrmann et al. (1997) and is based on the fact that the

http://www.astro.uu.se/~barklem/hlinop.html
The non-LTE corrections for neutral and singly-ionised magnesium were carried out using the codes DETAIL and SURFACE, originally developed by Giddings (1981) and Butler (1984), along with the model atmosphere computed with LLMODELS. Our calculations take into account the recent improvements in the atomic data for Mg, the extensive description of the model atom, and non-LTE line formation presented by Przybilla et al. (2001).

For both stars the non-LTE abundance correction \( \Delta(Mg/N_{\text{tot}})^{\text{NLTE}} = \log (Mg/N_{\text{tot}})^{\text{NLTE}} - \log (Mg/N_{\text{tot}})^{\text{LTE}} \) is +0.02 dex for the Mg lines at \( \lambda 5172 \) and \( \lambda 5252 \) Å, while for the Mg \( \iota \) line in line at \( \lambda 7877 \) Å we obtained a correction of −0.07 dex, in agreement with the results by Abia & Mashonkina (2004) and Przybilla et al. (2001).

In HD 32115 for the Mg \( \iota \) line at 5528 Å we obtained a LTE abundance of \( \log (Mg/N_{\text{tot}})^{\text{LTE}} = -4.50 \), therefore \( \log (Mg/N_{\text{tot}})^{\text{NLTE}} = -4.48 \). Similarly, for the Mg \( \iota \) line at \( \lambda 7877 \) Å we obtained a LTE abundance of \( \log (Mg/N_{\text{tot}})^{\text{LTE}} = -4.39 \), therefore \( \log (Mg/N_{\text{tot}})^{\text{NLTE}} = -4.46 \). Spectral synthesis in the region of the weaker Mg \( \iota \) lines at \( \lambda \lambda 4390 \) and 4427 Å, are not sensitive to non-LTE effects, requires an abundance in close agreement with that derived from the Mg \( \iota \) lines. Therefore to perform the fit of the line wings of the Mg \( \iota \) line at 5172 Å line, we set the Mg abundance for HD 32115 at −4.48, in non-LTE, and −4.50, in LTE.

For HD 37954, non-LTE corrections are similar to those in HD 32115, in particular they are identical for both Mg \( \iota \) lines at \( \lambda 5528 \) Å and \( \lambda 5172 \) Å. Therefore we applied for the fitting of the Mg \( \iota \) line at 5172 Å line wings the LTE Mg abundance derived from the Mg \( \iota \) line at \( \lambda 5172 \) Å line: \( \log (Mg/N_{\text{tot}})^{\text{LTE}} = -4.77 \).

To derive \( \log g \) from the fit of the Mg \( \iota \) lines with extended wings, very accurate \( \log gf \) values and Van der Waals (log \( \gamma_{\text{Va}} \)) damping constants are needed. Two sets of \( \log gf \) laboratory measurements for the Mg \( \iota \) triplet are available. The first one based on the lifetime laboratory measurements (Anderson et al. 1967) came from the VALD database, while the second set, based on lifetimes and branching ratio measurements was recently published by Aldénius et al. (2007). The accuracy of this set of transition probabilities is \( \sigma(\log gf) \approx \pm 0.04 \) dex. Van der Waals damping constants in VALD are calculated by Barklem & O'Mara (2000). Another estimate of \( (\log \gamma_{\text{Va}}) \) was given by Fuhrmann et al. (1997), who derived \( \log \gamma_{\text{Va}} = -7.42 \) from the fitting of the solar lines using the Anderson et al. (1967) oscillator strengths. Fuhrmann et al. (1997)
noted that Stark broadening does not practically influence the Mg line profiles in the solar spectrum and in Procyon, while it might be more significant in hotter stars. For our analysis we employed Stark damping constant $\log \gamma_{\text{Stark}} = -5.44$ for the Mg triplet and $\log \gamma_{\text{Stark}} = -4.63$ for the Mg $\lambda 5528$ Å line calculated by Dimitrijević & Sahal-Bréchot (1994). Our calculations show that the line profile of the latter line in the spectra of both HD 32115 and HD 37594 is not sensitive to Stark and Van der Waals broadening effects.

First, we checked the atomic parameters on the NSO solar flux atlas (Kurucz et al. 1984). LTE synthetic spectrum calculations in the region of the Mg triplet and of the Mg $\lambda 5528$ Å line were performed for three different models of the solar atmosphere: MARCS (Gustafsson et al. 2008), MAFAGS (Grupp et al. 2009), and the one calculated with the LLModels code. We fit the extended wings, not the cores of these lines which are subject to non-LTE effects. Using $\log \gamma_{\text{wide}}$ from Barklem & O’Mara (2000) and $\log \gamma_{\text{tot}}$ from Aldenius et al. (2007), we derived the following LTE Mg abundance in the solar atmosphere: log(Mg/Ne) = -4.54 (MARCS), -4.55 (MAFAGS), and -4.51 (LLModels). It corresponds to 7.50, 7.49 and 7.53 in logarithmic scale where $\log(H)$=12.00. Our estimates are closer to the Mg meteoritic abundance of 7.53±0.01 (Lodders et al. 2009), then to the most recent published value of the Mg abundance of 7.60±0.04 in the solar photosphere (Asplund et al. 2009).

For HD 32115 and HD 37594, careful fit of the Mg $\lambda 5172$ Å profile, calculated with the transition probabilities from Aldenius et al. (2007) and damping constants from Barklem & O’Mara (2000) and Dimitrijević & Sahal-Bréchot (1994), results in the final value of $\log g=4.2\pm 0.1$, in good agreement also with the gravity estimates from the photometric calibrations. Error estimates include the claimed ±30% error in the Stark damping constant calculations and also the possible errors in other spectral line parameters. The $\log g$ value of 4.2±0.1 is also in very good agreement with the results obtained by both Fekel et al. (2006) and Allende Prieto & Lambert (1999) for HD 32115.

Figure 3 shows comparisons for HD 32115 and HD 37594 between the observed and synthetic line profile of the $\lambda 5172$ Å Mg line, calculated adopting the oscillator strength from Aldenius et al. (2007) and damping constant from Barklem & O’Mara (2000). The synthetic profiles calculated with the parameters and abundances by B08 are also shown (B08 adopted oscillator strength and damping constant given in VALD).

Figure 3 shows an excellent agreement between the synthetic profiles calculated with our final adopted parameters and the observed spectrum. On the other hand, the synthetic profiles calculated with B08’s parameters display a disagreement with the observations, in particular for HD 32115. For HD 37594 the discrepancy is rather small: the effect of the higher $T_{\text{eff}}$ is mostly compensated by the lower gravity.

The other two Mg lines of the triplet ($\lambda \lambda 5167$ and 5183 Å) will provide the same results we obtained with the $\lambda 5172$ Å Mg line, as tested by R09 with the Sun, Procyon and HD 49933.

For HD 32115, we used the stellar mass and bolometric magnitude by Fekel et al. (2006), in addition to our $T_{\text{eff}}$, to derive $\log g$: $\log g(\gamma_{\text{g}}) = \log(M/M_{\odot}) + 4 \cdot \log(T_{\text{eff}}/T_{\odot}) + 0.4 \cdot (M_{\text{bol}} - 4.75)$. We obtained a $\log g$ value of 4.24, in good agreement with our previous estimation and with the results by Fekel et al. (2006) and Allende Prieto & Lambert (1999).

Figure 3. Comparison between the observed Mg line profile of the line at $\lambda 5172$ Å (black solid line) and synthetic profiles calculated with our final adopted parameters (red dashed line) and with the parameters adopted by B08 (blue dotted line). The upper comparison is for HD 37594, while the lower comparison is for HD 32115. The profiles shown for HD 37594 were rigidly shifted upwards of 0.3. Our synthetic profiles are calculated adopting the oscillator strength from Aldenius et al. (2007), damping constant from Barklem & O’Mara (2000) and a LTE Mg abundance of -4.50 dex for HD 32115 and -4.77 dex for HD 37594. B08 does not provide a Mg abundance for HD 37594, therefore we derived it from the Mg $\lambda 12528$ Å, adopting the parameters given in their paper.

### 3.2.3 Metallic lines

The metallic-line spectrum provides further constraints on the atmospheric parameters. If no deviation from LTE is expected, there should be no trend in individual line abundances as a function of excitation potential. Examining this for any element/ion therefore provides a check on the determined value of $T_{\text{eff}}$. The balance between different ionisation stages of the same element similarly provides a check on $\log g$. The microturbulent velocity ($v_{\text{mic}}$) is subsequently determined by minimising any trend between individual abundances and equivalent widths for a certain ion. Determining the fundamental parameters in this way must be done iteratively since, for example, a variation in $T_{\text{eff}}$ leads to a change in the best $\log g$ and $v_{\text{mic}}$. This methodology of fundamental parameter determination from the metallic-line spectrum is adopted in almost all semi-automatic abundance analysis procedures (e.g. Bruntt et al. 2002, Santos et al. 2004, Gillon & Magain 2006).

The analysis of the metallic line spectrum requires the best possible knowledge of atomic line parameters, $\log gf$ values in particular. In this work we only use lines of Ca, Ti, Cr, and Fe for which experimental atomic parameters are available (except for Cr II, as clarified later in the text). Atomic parameters were extracted from the VALD database and from other recent publications, see references in Table 4.

Data for neutral and ionised Ca lines were validated with non-LTE calculations by Mashonkina et al. (2007). For Ti I, Ti II, Cr I and Fe I lines, accurate laboratory data (lifetimes and branching ratios) are available. For lines of ionised iron the oscillator strengths, selected from VALD, were produced from laboratory data, as explained by Ryabchikova et al. (1999). All corresponding references are given in Table 4. Laboratory data for optical Cr II lines are scarce, therefore we took into account two differ-
ent sets of calculated data, the one from semi-empirical orthogonal operator calculations by [Raassen & Uylings 1998], and the one from the latest calculations by R. Kurucz. The lifetimes calculated by the two groups agree very well and are very close to recent laboratory lifetime measurements by [Nilsson et al. 2006] and [Gurell et al. 2010]. A small difference between theoretical and experimental lifetimes, converted to a difference in oscillator strength, corresponds to a log g-f-value uncertainty no larger than ±0.03 dex. However, the two sets of calculated oscillator strengths, for the lines used in our analysis, differ by 0.2 dex, as a result of different branching factors, as the lifetimes are practically identical. From two theoretical sets of oscillator strengths, [Raassen & Uylings 1998]'s data provide us with a smaller standard deviation from the mean Cr abundance, while Kurucz's data give a mean abundance closer to that derived from the Cr lines. Clearly, an extensive laboratory analysis of Cr lines in the optical region is needed for the interpretation of the Cr abundance in atmospheres of cool and hot stars.

LTE line abundances were based on equivalent widths, analysed with a modified version [tymhuba1996] of the WIDTH9 code [Kurucz 1993]. For blended lines and lines situated in the wings of the hydrogen lines we derived the line abundance performing synthetic spectrum calculations with the SYNTH3 code, tuning g_max line by line (see Sect.4.2.2). A line-by-line abundance list with the equivalent width measurements, adopted oscillator strengths, and their sources is given in Table 4 (see the online material for the complete version of the table). Table 4 also gives equivalent width measurements for the lines which we measured via spectral synthesis. In these cases, equivalent widths were tuned to match the abundance obtained with spectral synthesis. Our analysis shows that it is practically impossible to get a unique value of the microturbulent velocity for all considered species, therefore we derive a value that satisfies all the data and still provides a small scatter.

Figures 4 and 5 show the correlations of Fe i and Fe ii abundance with equivalent width (left panels) and with excitation potential (right panels), respectively for HD 32115 and HD 37594. In each Figure, we used our final adopted fundamental parameters for the top panels and B08's fundamental parameters for the bottom panels. B08 derived the effective temperature by imposing the excitation equilibrium for the Fe i lines only, the surface gravity by imposing the ionisation equilibrium for Fe i only, and the microturbulence velocity by removing the correlation between abundance and equivalent widths for Fe i lines only.

With our model parameters for HD 32115, we get a small positive correlation for Fe i abundance, and a small anti-correlation for Fe ii abundance, with the excitation potential. Our adopted T_eff thus accommodates both Fe i and Fe ii. With our model parameters for HD 37594, we get a small positive correlation for both Fe i and Fe ii abundance with the excitation potential. These correlations would change slightly by adopting a different set of Fe lines, even by adding or removing a few lines, making the parameter determination based on these correlations rather sensitive to systematic effects introduced by the line selection. One example is the high excitation energy Fe ii line, shown in Figs. 4 and 5 which has a much larger influence on the Fe ii excitation equilibrium, compared to the other Fe ii lines.

The model parameters obtained by B08 lead to almost perfect equilibria for Fe i, as requested by B08 analysis method; in the case of HD 32115, B08's T_eff is anyway so high that even the excitation equilibrium for Fe i is not reached, although it is imposed by their analysis method.

The equilibria for Fe i are reached better with B08's parameters, compared to ours, as it is the only T_eff and u_mic indicator they used, but it leads to a set of parameters which does not fit all the other parameter indicators, first of all Fe ii.

The average abundances, shown in Figs. 4 and 5, show that we obtain the ionisation equilibrium for Fe i, within the error bars. We notice also that our average Fe ii abundance is systematically higher by a few 0.01 dex, compared to Fe i, in agreement with non-LTE calculations by [Mashonkina 2011] (the direction of the Fe non-LTE corrections is shown in Figs. 4 and 5). Adopting B08's parameters, we obtain a systematically lower Fe ii abundance, compared to ours, as it is the only T_eff and u_mic indicator they used, but it leads to a set of parameters which does not fit all the other parameter indicators, first of all Fe ii.

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Table 2. Lines used for the parameter determination. Wavelengths and excitation potentials are taken from the VALD database. The adopted log $g_f$ values are taken from different sources which are listed in the last column. "S" in the equivalent with column denotes line abundances determined by fitting the observed line profile, with the equivalent width determined from the line abundance. The log $g_f$ values by Blackwell et al. (1980) and Baschek et al. (1970) were corrected by +0.2 and +0.16, respectively. For Cr II the results obtained with two different sets of log $g_f$ values are given (see the Sect. 3.2.3). For each ion, the last line gives the average abundance and the standard deviation, with the number of lines in parenthesis. The entire table can be viewed in the electronic version of the Journal.

| Element | HD 37594 | HD 32115 |
|---------|----------|----------|
| Wavelength | $\chi_{\text{excit}}$ | log $g_f$ | EQW abundance | log $g_f$ | EQW abundance | Ref log $g_f$ |
| Ca i | 4425.4370 | 1.8790 | -0.358 | S | 100.0 | -6.00 | 112.71 | -5.70 | SN |
| | 4435.6790 | 1.8860 | -0.517 | S | 90.0 | -6.00 | 54.80 | -5.78 | SR |
| | 4526.9280 | 2.7090 | -0.548 | 54.80 | -5.78 | SR |
| | 4578.5510 | 2.5210 | -0.697 | 43.00 | -5.98 | 27.60 | -5.70 | S |
| | 5261.7040 | 2.5210 | -0.579 | S | 46.0 | -6.08 | SR |
| | 5512.9800 | 2.9330 | -0.464 | 39.77 | -6.00 | 47.26 | -5.83 | SR+Sm |
| | 5581.9650 | 2.5230 | -0.555 | 55.26 | -5.97 | 64.10 | -5.78 | SR+Sm |
| | 5588.7490 | 2.5260 | 0.358 | 125.68 | -5.84 | SR+Sm |

... ... ... ... ... ... ...

S - Smith (1988); Sm - Smith (1981); SN - Smith & O'Neil (1975); SR - Smith & Raggett (1981);

...pared to Fe i, and the non-LTE corrections by Mashonkina (2011) would then worsen the ionisation equilibrium, indicating that B08’s sets of parameters is inappropriate for these stars.

Figure 6 shows the line abundance versus the equivalent widths for Ca, Ti, and Cr, in HD 32115 and HD 37594, adopting our final fundamental parameters. As for Fe, these elements display a variety of small correlations and on average our fundamental parameters are the ones which suit at best all considered ions. The ionisation equilibrium is reached within the error bars for all elements considered here, except Cr, for which the equilibrium is obtained adopting Kurucz’s oscillator strengths, as shown in Table 4. Also with laboratory data for Cr lines, we expect an improvement in the Cr ionisation equilibrium.

4 DISCUSSION

For HD 32115 our final adopted set of parameters is: $T_{\text{eff}} = 7250 \pm 100$ K, log $g = 4.2 \pm 0.1$ and $v_{\text{mic}} = 2.5 \pm 0.2$ km s$^{-1}$. For HD 37594 we derived $T_{\text{eff}} = 7150 \pm 100$ K, log $g = 4.2 \pm 0.1$ and $v_{\text{mic}} = 2.6 \pm 0.2$ km s$^{-1}$. The measured projected rotational velocity ($v \sin i$) is 8.3 and 17.0 km s$^{-1}$, respectively for HD 32115 and HD 37594. The observed line profiles required also a substantial macroturbulence velocity ($v_{\text{macro}}$), generally between 8 and 10 km s$^{-1}$ for both stars (see Sect. 4.2 for more details). These high values of $v_{\text{macro}}$ are in line with an extrapolation of the $v_{\text{macro}}$ - $T_{\text{eff}}$ correlations given by Valenti & Fisher (2005) and Bruntt et al. (2010).

Our fundamental parameters are not perfect, by definition, but they provide, within the error bars, the best description of all available observables: photometric colors, hydrogen and metallic line profiles.

Figure 6. Individual abundances for Ca (top panels), Ti (middle panels), and Cr (bottom panels) lines versus the equivalent width measured for HD 32115 (left panels) and HD 37594 (right panels). In each panel, the black crosses indicate the lines of neutral elements, while the red asterisks indicate the lines of singly ionised elements. All abundances are derived assuming our adopted fundamental parameters. The linear fits to the data are also shown. The black cross and red asterisk at negative equivalent widths show the average abundance respectively for the neutral and singly ionised elements, with their standard deviation. The poor Cr ionisation equilibrium is most likely due to the poor quality line data.

4.1 Model fluxes and observed photometry

Other methods which should always be used to check the fundamental parameters obtained by spectroscopic means are: i) comparison of synthetic and observed optical colors; ii) comparison be-
metric filters, mirror reflectivity and a photomultiplier response were calculated using modified computer codes by Kurucz (1993), which are based on the low resolution theoretical fluxes, our function. In contrast to Kurucz’s procedures (Relyea & Kurucz 1978) which take into account transmission curves of individual photometric filters, mirror reflectivity and a photomultiplier response function. In contrast to Kurucz’s procedures (Relyea & Kurucz 1978), which are based on the low resolution theoretical fluxes, our synthetic colors are computed from energy distributions sampled with a fine wavelength step, so integration errors are expected to be small.

To fully understand Table [B] it is first necessary to establish more in general how well synthetic colors can reproduce the observations. This can be done by comparing synthetic and observed colors for well known stars. To check the quality of synthetic and observed colors over a large temperature range, we examine three “standard” stars with different temperatures: Procyon (T eff =6530 K; Fuhrmann et al. 1997), Vega (T eff =9550 K; Castelli & Kurucz 1994), and 21 Peg (T eff =10400 K; Fossati et al. 2009).

Figure 7 shows a comparison between synthetic and observed colors for the three reference stars, plus HD 32115 and HD 37594. With a few exceptions, there is general good agreement between synthetic and observed colors throughout the temperature region explored here. For 21 Peg, there is difference of 0.04 mag between synthetic and observed U − B Johnson color, V1 − B and G − B Geneva colors. This difference is most likely due to incorrect photometry in one (or more) photometric band, as there is a perfect agreement between synthetic spectral energy distribution and spectrophotometry in the whole wavelength region between the near-UV and the near infrared (see Fig. 4 by Fossati et al. 2009). On the other hand we do not have an explanation for the difference of 0.03 mag obtained between synthetic and observed b − y Strömgren color for Procyon, although an error in the photometry is always possible, even for such a bright star. Besides these two exceptions, there is general agreement between synthetic and observed colors at a 0.01–0.02 mag level, which represents then the typical precision that one can expect for the comparison between observed and synthetic colors.

Figure 7 shows that for HD 32115 and HD 37594 the difference between synthetic and observed colors is within the typical precision obtained for the “reference” stars, confirming the quality of our fundamental parameters. Figure 8 shows a comparison between observed and synthetic colors calculated with B08’s stellar parameters clearly demonstrate the inadequacy of the B08 fundamental parameters.

4.1.2 Spectral energy distribution

For a complete self-consistent analysis of any star, one should reproduce the observed spectral energy distribution with the adopted parameters for a model atmosphere. For HD 32115 and HD 37594 no spectrophotometry is available, therefore we converted the available Johnson (Johnson et al. 1966), Geneva (Rufenec 1988) and 2MASS (Zacharias et al. 2005) photometry into physical units and compared them with the model fluxes calculated with the final set of parameters derived for the two stars. In the case of the Geneva colors, we assumed that Geneva V1 index is close to Johnson V1, making then possible to recover the Geneva B index and thus U, B1, B2, V1, and G, and to transform them to absolute fluxes using the calibrations given by Rufenec & Nicolet (1988). For the 2MASS (JHK) photometry we employed calibrations by
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Table 3. Observed and calculated photometric parameters of HD 32115 and HD 37594. The values in brackets give the error bars of observations. The better agreeing theoretical index in each case is highlighted.

|  | Observed photometry | HD 32115 t7250g4.2 this work | t7670g4.44 B08 | HD 37594 t7150g4.20 this work | t7380g4.08 B08 |
|---|---|---|---|---|---|
| **Johnson** | | | | | |
| U-B | 0.040 | 0.0316 | 0.0368 | 0.010 | 0.0002 | 0.0290 |
| B-V | 0.285 | **0.2943** | 0.2432 | 0.275 | **0.2964** | 0.2530 |
| **Strömgren** | | | | | |
| b-y | 0.176 | 0.1904 | 0.1463 | 0.189 | 0.1982 | 0.1668 |
| m1 | 0.181 | **0.1787** | 0.2023 | 0.160 | **0.1621** | 0.1674 |
| c1 | 0.689 | **0.7044** | 0.7399 | 0.669 | **0.6806** | 0.7832 |
| Hβ | 2.753 | **2.8077** | 2.8502 | 2.738 | **2.7924** | 2.8180 |
| **Geneva** | | | | | |
| U-B | 1.389 | **1.3972** | 1.4041 | 1.354 | **1.3646** | 1.4298 |
| V-B | 0.611 | **0.6160** | 0.6732 | 0.606 | **0.6161** | 0.6658 |
| B1-B | 0.963 | 0.9823 | **0.9769** | 0.950 | 0.9728 | **0.9639** |
| B2-B | 1.416 | **1.4190** | 1.4255 | 1.423 | **1.4273** | 1.4371 |
| V1-B | 1.328 | **1.3371** | 1.3901 | 1.324 | **1.3376** | 1.3844 |
| G-B | 1.734 | **1.7478** | 1.8217 | 1.720 | **1.7465** | 1.8077 |

van der Bliek et al. (1996), while for the Johnson photometry we employed calibrations by Bessell et al. (1998).

Figure 9 shows the comparison between the observed photometry (in physical units) and the model fluxes calculated with the adopted atmospheric parameters for HD 32115 and HD 37594. There is a good agreement between observed and synthetic fluxes in the visible and infrared regions, providing a further confirmation of our adopted stellar parameters for the two stars.

Precise HIPPARCOS parallaxes are available for both stars (van Leeuwen 2007). This allowed us also to estimate their radii: 1.52±0.04 Rsun for HD 32115 and 1.36±0.02 Rsun for HD 37594. The radius we derived for HD 32115 is in very good agreement with what previously obtained by Fekel et al. (2006) and Allende Prieto et al. (1999), who measured the stellar radius by means of stellar evolution calculations. This comparison increases the confidence on our results.

4.2 Classic vs. semi-automatic procedures

The most evident difference between the analysis performed by B08 and our analysis (including HD 49933 by R09) is that B08 did not add any \( \upsilon_{macro} \) to the line broadening. Since B08 used line profile fitting, instead of equivalent widths, the lack of the additional broadening renders their whole analysis questionable. Bikmaev et al. (2002) also did not use any \( \upsilon_{macro} \) in their analysis, but their spectra were of mid-low resolution and therefore \( \upsilon \sin i \) was enough to fit the lines and their abundance analysis was based mainly on equivalent widths, independent of \( \upsilon_{macro} \). At the resolution of CORALIE and TS (R=50 000 and 60 000, respectively), line profiles clearly require an additional \( \upsilon_{macro} \) broadening.

Figure 10 compares the observed HD 32115 line profiles of two Fe II lines, one weak and one strong, with three synthetic spectra calculated with our adopted parameters and three different sets of broadening parameters. The three broadening parameter sets are suited to weak lines, strong lines, and one as given by B08, respectively.

The difference in \( \upsilon_{macro} \) between weak and strong lines is found systematically for several lines of the same ion, and for
different ions, excluding the possibility that this is due to an error in $\nu_{\text{mic}}$, $\nu_{\sin i}$, or in the damping constants (homogeneous calculations by Barklem et al. 2000; Barklem & Aspelund-Johansson 2005). This systematic difference in $\nu_{\text{macro}}$ between weak and strong lines was found also by Fuhrmann et al. (1997) in their analysis of Procyon.

The profiles calculated using the broadening by B08 show too deep cores and too narrow wings. This implies that B08 systematically obtained erroneously high $T_{\text{eff}}$ for the three stars (HD 49933, HD 32115, and HD 37594) to compensate for the deeper line cores, as a result of neglecting $\nu_{\text{macro}}$ and fitting line cores to derive the abundances. This is confirmed by the fact that Bruntt (2009) reanalysed HD 49933, adopting a $\nu_{\text{macro}}$ of 2 km s$^{-1}$, and obtained a much lower temperature than given in B08. It is still not clear to us where this particular value of $\nu_{\text{macro}}$ came from, as R09 measured a $\nu_{\text{macro}}$ of 5.2±0.5 km s$^{-1}$, in agreement with the calibration by Valenti & Fisher (2005). Figure 10 demonstrates that even adopting all the parameters and abundances given by B08, it is impossible to simultaneously fit the line profiles of weak and strong lines, as the wings will always be too narrow and the higher $T_{\text{eff}}$ cannot compensate for it.

One of our main goals was to find and analyse possible sources of discrepancies between the results obtained with a classical method of analysis (e.g. this work and R09) and with a semi-automatic procedure (e.g. Bruntt et al. 2008; Bruntt 2009). We have identified two possible sources of discrepancy. The first arises from semi-automatic procedures often taking into account only Fe i lines to derive $T_{\text{eff}}$ and $\nu_{\text{mic}}$, while the second arises from the nature of the line profiles for these stars.

4.2.1 Is Fe i alone good enough for a precise parameter determination?

The upper-left panel of Fig. 4 shows the Fe i and Fe ii line abundance as a function of equivalent width, used for the determination of the microturbulence velocity. It is clear that a perfect equilibrium
between the line abundance and equivalent width is not reached, and not simultaneously reachable, as the two ions show opposite correlations: $-5.252 \pm 2.407$ and $6.402 \pm 3.676$, in units of $10^{-5}$, respectively for Fe i and Fe ii. Something similar is found for the ions of other species, as both Ca and Cr show a positive correlation, while Ti shows a negative correlation (see Fig. 6).

The $v_{\text{mic}}$ value we adopted considers the effects on all the ions we took into account, whereas the $v_{\text{mic}}$ value derived from the Fe i lines alone, worsens the situation for Fe ii and Ti, resulting in a systematic underestimation of $v_{\text{mic}}$ (Bruntt et al. 2010) presented a calibration of $v_{\text{mic}}$ as a function of $T_{\text{eff}}$ for late-type stars, based on the analysis of Fe i lines alone, therefore this calibration could also underestimate $v_{\text{mic}}$.

Using Fe i lines alone for the determination of $v_{\text{mic}}$ means that the average Fe abundance depends strongly on which lines have been selected. If the selected Fe ii lines are predominantly weak, the Fe ii abundance will be artificially low. This introduces a bias in the determination of the surface gravity, as most semi-automatic procedures employ the Fe ionisation equilibrium alone to measure log $g$. The use of predominant medium-to-weak Fe ii lines, with the adoption of Fe i lines alone to determine $v_{\text{mic}}$ Consequently leads to a systematically erroneously low Fe ii abundance, which then causes an erroneously high log $g$ to be inferred. This of course, then affects the value of $T_{\text{eff}}$.

Another problem connected to the use of Fe i lines as the sole temperature indicator is shown in the top-right panel of Fig. 6. The effective temperature which best fits all available observables does not completely remove the correlation between abundance and excitation potential. For HD 32115, by adopting only Fe i as a $T_{\text{eff}}$ and $v_{\text{mic}}$ indicator, and only Fe for the ionisation equilibrium, we derived $T_{\text{eff}}=7400\,\text{K}$, log g=4.2, and $v_{\text{mic}}=2.4\,\text{km\,s}^{-1}$. Similarly, for HD 37594 we obtained $T_{\text{eff}}=7300\,\text{K}$, log g=4.1, and $v_{\text{mic}}=2.5\,\text{km\,s}^{-1}$. These temperatures are too high and cannot fit the hydrogen lines or the photometry, with photometric colors revealing the discrepancies.

The adoption of Fe i alone as $T_{\text{eff}}$ and $v_{\text{mic}}$ indicator might also lead to the presence of systematic errors in the fundamental parameters arising from non-LTE effects. This is particularly true for cool stars, where non-LTE effects are larger for Fe i than Fe ii, with obvious consequences for i.e. log $g$. Non-LTE effects are generally stronger for stronger lines, implying that systematic errors might be introduced in the determination of $v_{\text{mic}}$, consequently affecting $T_{\text{eff}}$ as well.

All problems described here can be solved by including other ions in the process of parameter determination. Although fewer lines of ions other than Fe i are usually available, their inclusion in the parameter determination procedure would significantly alleviate the systematic errors introduced by the use of only Fe i lines. Asplund et al. (2005) shows differences between 3D and 1D LTE abundances for several ions as a function of the excitation potential for the Sun. For Fe i, the 1D models, compared to the 3D models, lead to a deviation as large as 0.2 dex for the low excitation lines, which decreases with increasing excitation potential. Clearly, the use of 1D models introduces a strong bias towards high temperatures. This effect is present, with slightly different strengths, for many other ions. It would be extremely valuable to study this effect for stars hotter than the Sun, where the registered high $v_{\text{macro}}$ Values suggest that hydrodynamical effects might be even stronger than in the Sun.

### 4.2.2 The effect of macroturbulence

Valenti & Fisher (2005) and Bruntt et al. (2010) showed that for late-type stars the macroturbulence velocity ($v_{\text{macro}}$) increases with increasing $T_{\text{eff}}$. For HD 32115 and HD 37594, $v_{\text{macro}}$ reaches rather high values, close to $10\,\text{km\,s}^{-1}$. During the analysis of the spectra of the two stars, we noticed a systematic difference between the line profiles of strong and weak lines, as strong lines require a systematically higher $v_{\text{macro}}$ compared to weak lines, by $\sim 2\,\text{km\,s}^{-1}$, as shown in Fig. 10. We believe that this difference is due to unmodelled depth-dependent velocities in the atmosphere which become evident for stars with relatively high $v_{\text{macro}}$ and low $\nu\sin i$.

This is not a concern if the abundances are derived from equivalent widths, as they are independent of macroturbulence velocity. On the other hand, if the abundances are obtained from line profile fitting, where the abundance is the only free parameter, a systematic abundance difference is introduced between strong and weak lines, affecting the determination of the fundamental parameters.

Semi-automatic abundance analysis procedures first set the broadening parameters to the entire available spectrum and then measure the line abundance from line profile fitting. If strong and weak lines require different broadening, opposing biases are introduced in the abundances derived from weak and strong lines. We estimated that the abundances obtained by fitting the profile of strong lines, adopting a $v_{\text{macro}}$ typical for weak lines, are systematically lower by 0.10–0.15 dex, compared to the abundances obtained with a $v_{\text{macro}}$ appropriate to strong lines. Consequently the abundances obtained from weak and strong lines will be systematically over- and under-estimated, respectively.

The systematic effect described above might be temperature and $\nu\sin i$ dependent as the difference in $v_{\text{macro}}$, between weak and strong lines could increase with increasing $T_{\text{eff}}$, and be more evident with decreasing $\nu\sin i$. In fact, the worst situation may be for slowly rotating “cool” early-type stars, such as HD 32115.

The problem described here can be solved using equivalent widths, instead of line profile fitting, as the equivalent widths are broadening independent. Alternatively $v_{\text{macro}}$ could be treated as a further free parameter in the line profile fitting, although thorough tests on the uniqueness of the derived line abundance and $v_{\text{macro}}$ should be performed. The adoption of 3D atmosphere models would also partly eliminate this problem, but this is not a viable solution for an abundance analysis of a large sample of stars.

### 5 Conclusion

On the basis of high resolution, high signal-to-noise ratio spectra, taken at the McDonald observatory, we carried out a precise parameter determination of two late A-type stars, HD 32115 and HD 37594, which Bruntt et al. (2008) adopted as reference stars for their abundance analysis of $\gamma$ Dor stars. Bruntt et al. (2008) analysed these stars with a semi-automatic procedure and their results strongly disagreed with those previously obtained by Bikmaev et al. (2002), by means of a “classical” analysis. This discrepancy, together with that previously highlighted by Ryabchikova et al. (2009) for HD 49933, prompted us to reanalyse HD 32115 and HD 37594 to look for the origin of the discrepancies.

We derived the fundamental parameters making use of all the available observables: multicolor photometry, pressure-sensitive magnesium lines, metallic lines and profiles of hydrogen Balmer lines. For HD 32115 our final adopted set of parameters is: $T_{\text{eff}} = 7250\pm100\,\text{K}$, log g = 4.2$\pm 0.1$ and $v_{\text{mic}} = 2.5\pm 0.2\,\text{km\,s}^{-1}$. For
HD 37594 we adopted: $T_{\text{eff}} = 7150 \pm 100$ K, $\log g = 4.2 \pm 0.1$ and $\upsilon_{\text{mic}} = 2.6 \pm 0.2$ km s$^{-1}$. We confirmed our final set of parameters by comparing flux calibrated photometry with spectral synthetic energy distributions, and by comparing observed and synthetic photometric colors. Our preferred fundamental parameters fit, within the error bars, all available observables. They are also in agreement with the results by Bikmaev et al. (2002), but disagree with the results by Bruntt et al. (2008). For HD 32115, our set of parameters agrees with that previously obtained by Fekel et al. (2006) and Allende Prieto & Lambert (1999). In addition, the radius of HD 32115, we derived from the analysis of the spectral energy distribution, is in perfect agreement with that derived by Fekel et al. (2006). For HD 32115, our set of parameters agrees with that previously obtained by Fekel et al. (2006) and Allende Prieto & Lambert (1999) by means of stellar evolution calculations.

We compared our McDonald spectra with those used by Bruntt et al. (2008) and Bikmaev et al. (2002), concluding that the differences between the three set of spectra is well within the given S/N. The quality of the data is not the origin of the discrepancies.

To fit the line profiles of the two stars, we had to adopt rather large $\upsilon_{\text{mic}}$ values, between 8 and 10 km s$^{-1}$. Although the spectra analysed by Bruntt et al. (2008) had enough resolution to require the need of $\upsilon_{\text{mic}}$ to fit line profiles, they adopted only rotational broadening ($\upsilon_{\text{rot}}$) in their spectral synthesis. As a consequence, by deriving the line abundance by fitting synthetic line profiles to the observed ones, discarding any $\upsilon_{\text{mic}}$ broadening, they introduced a bias in their analysis, which we believe led them to an erroneous set of fundamental parameters.

We have demonstrated that the determination of $T_{\text{eff}}$ and $\log g$ using only the Fe i excitation equilibrium and the Fe ionisation equilibrium leads to a systematic higher $T_{\text{eff}}$ compared to that suggested by all other indicators. We also believe that this effect might be temperature dependent.

Several automatic and semi-automatic procedures use the Fe i excitation equilibrium and the Fe ionisation equilibrium as only/primary indicators for stellar parameter determination. In this work we show that these procedures do not always provide the correct set of fundamental parameters and their results need to be cautiously taken when performing further analysis, such as modelling of the asteroseismic frequencies or the characterisation of transiting exoplanets.

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Table 4: Lines used for the parameter determination. Wavelengths and excitation potentials are taken from the VALD database. The adopted log \(g_f\) values are taken from different sources which are listed in the last column. “S” in the equivalent with column denotes line abundances determined by fitting the observed line profile, with the equivalent width determined from the line abundance. The log \(g_f\) values by Blackwell et al. (1980) and Baschek et al. (1970) were corrected by +0.2 and +0.16, respectively. For Cr\(ii\) the results obtained with two different sets of log \(g_f\) values are given (see the Sect. 3.2.3). For each ion, the last line gives the average abundance and the standard deviation, with the number of lines in parenthesis.

| Element | HD 37594 | HD 32115 | Ref log \(g_f\) |
|---------|----------|----------|----------------|
| Wavelength | \(\chi_{\text{exc}}\) eV | log \(g_f\) | EQW abundance | HD 37594 mÅ | HD 32115 mÅ | Eqw abundance | dex | dex | |
| Ca\(i\) | | | | | | | | | |
| 4425.4370 | 1.8790 | -0.358 | $S$ | 100.0 | -6.00 | 112.71 | -5.70 | SN |
| 4435.6790 | 2.0900 | -0.548 | 43.00 | 5.99 | 54.75 | -5.75 | SR+Sm |
| 4578.5510 | 2.5210 | -0.697 | 21.46 | 5.90 | 27.60 | -5.70 | S |
| 4685.2680 | 2.9330 | -0.879 | $S$ | 4.60 | 6.08 | 10.26 | -5.80 | SN |
| 5512.9800 | 2.5210 | -0.571 | 39.77 | 6.00 | 47.26 | -5.83 | SR+Sm |
| 5581.9650 | 2.5260 | -0.555 | 55.26 | 5.97 | 64.10 | -5.75 | SR+Sm |
| 5588.7490 | 2.5260 | 0.358 | 125.68 | 5.84 | | | |
| 5590.1140 | 2.5210 | -0.571 | 57.83 | 5.92 | 64.85 | -5.75 | SR+Sm |
| 5601.2770 | 2.5260 | -0.523 | 56.75 | 5.98 | 73.14 | -5.68 | SR+Sm |
| 5857.4510 | 2.9330 | -1.570 | 4.87 | 5.94 | 7.73 | -5.66 | S |
| 6122.2170 | 2.9330 | -0.316 | 123.55 | 5.80 | | | |
| 6161.2970 | 2.5230 | -1.266 | 13.42 | 6.09 | 23.49 | -5.74 | SR+Sm |
| 6162.1730 | 1.8990 | -0.090 | 144.67 | 5.74 | | | SN |
| 6166.4390 | 2.5210 | -1.142 | 24.02 | 5.92 | 30.20 | -5.73 | SR+Sm |
| 6169.0420 | 2.5230 | -0.797 | 32.57 | 6.10 | 52.80 | -5.71 | SR+Sm |
| 6169.5630 | 2.5260 | -0.478 | 72.66 | 5.83 | 74.77 | -5.73 | SR+Sm |
| 6471.6620 | 2.9330 | -1.570 | 4.87 | 5.94 | 7.73 | -5.66 | S |
| 6493.7810 | 2.5210 | -0.109 | 99.99 | 5.80 | | | |
| 6499.6500 | 2.5230 | -0.818 | 41.29 | 5.93 | | | |
| 6717.6810 | 2.7090 | -0.524 | 56.24 | 5.87 | | | |
| 7148.1500 | 2.5210 | -0.109 | 99.99 | 5.80 | | | |
| 7202.2000 | 2.5230 | -0.818 | 41.29 | 5.93 | | | |
| 7326.1450 | 2.9330 | -0.208 | 67.13 | 5.87 | 85.61 | -5.65 | S |
| Average | | | | -5.92±0.10 (25) | -5.71±0.06 (16) | |
| Ca\(ii\) | | | | | | | | | |
| 5001.4790 | 7.5050 | -0.507 | $S$ | 36.00 | 5.82 | 48.88 | -5.63 | TB |
| 5019.9710 | 7.5150 | -0.247 | 45.50 | 5.92 | | | TB |
| 5021.1380 | 7.5150 | -1.207 | 7.60 | 5.92 | 8.00 | -5.91 | TB |
| 5285.2660 | 7.5050 | -1.147 | $S$ | 11.10 | 5.80 | 16.40 | -5.62 | TB |
| 5339.1880 | 8.4380 | -0.079 | 25.50 | 5.79 | 40.00 | -5.60 | TB |
| 6456.8750 | 8.4380 | 0.421 | 61.00 | 5.64 | 80.00 | -5.58 | TB |
| 8201.7220 | 7.5050 | 0.368 | 100.00 | 5.72 | 125.03 | -5.50 | TB |
| 8248.7960 | 7.5150 | 0.556 | 163.00 | 5.57 | | | |
| 8254.7210 | 7.5150 | -0.398 | 57.00 | 5.72 | 68.79 | -5.60 | TB |
| Average | | | | -5.77±0.12 (9) | -5.64±0.13 (7) | | |
| Ti\(i\) | | | | | | | | | |
| 4453.6990 | 1.8730 | -0.354 | 17.07 | 7.34 | 20.80 | -7.14 | MFW |
| 4548.7630 | 2.4900 | 0.425 | 13.00 | 7.50 | 19.90 | -7.20 | MFW |
| 4617.2690 | 2.4900 | 0.389 | 13.00 | 7.50 | 19.90 | -7.20 | MFW |
| 4758.1180 | 2.4900 | 0.425 | 13.00 | 7.50 | 19.90 | -7.20 | MFW |
| 4759.2700 | 2.4900 | 0.389 | 13.00 | 7.50 | 19.90 | -7.20 | MFW |
| 4981.7310 | 0.8480 | 0.504 | 60.55 | 7.44 | 68.20 | -7.24 | MFW |

Average: -5.92±0.10 (25) -5.71±0.06 (16)
The accuracy of stellar atmospheric parameter determinations: a case study with HD 32115 and HD 37594

### Table 4: continued.

| Element | Wavelength Å | $\chi_{\text{excit}}$ eV | log g f | HD 37594 EQW abundance mÅ dex | HD 32115 EQW abundance mÅ dex | Ref log g f |
|---------|--------------|----------------|--------|-------------------------------|-------------------------------|-----------|
| Ti ii   | 4999.5030    | 0.8260         | 0.250  | 49.47 -7.36                   | 51.70 -7.23                   | MFW       |
|         | 5192.9690    | 0.0210         | -1.006 | 22.40 -7.23                   | 21.30 -7.15                   | MFW       |
|         | 5210.3850    | 0.0480         | -0.884 | 20.84 -7.36                   | 23.10 -7.21                   | MFW       |
|         | 6261.0980    | 1.4300         | -0.479 | 7.67 -7.19                    | 8.20 -7.07                    | MFW       |
| Average |              |                |        | -7.35 ±0.11 (7)               | -7.16 ±0.06 (10)              |           |
| Cr i    | 4274.7970    | 0.0000         | -0.231 | $142.0 -6.72$                 | $153.0 -6.37$                 | MFW       |
|         | 4545.9350    | 0.9410         | -1.370 | 22.29 -6.84                   | 34.0 -6.51                    | SLS       |
|         | 4492.3050    | 3.3750         | -0.392 | 9.32 -6.29                    | 3.46 -6.53                    | MFW       |
|         | 4616.1240    | 0.9830         | -1.190 | 28.18 -6.87                   | 41.63 -6.53                   | SLS       |
|         | 4646.1620    | 1.0300         | -0.740 | 68.94 -6.56                   | 41.63 -6.53                   | SLS       |
|         | 4651.2840    | 0.9830         | -1.460 | 18.32 -6.83                   | 27.65 -6.51                   | SLS       |
|         | 4652.1570    | 1.0040         | -1.040 | 41.90 -6.76                   | 53.42 -6.50                   | SLS       |
|         | 4689.3570    | 3.1250         | -0.400 | 11.00 -6.47                   | 15.33 -6.24                   | SLS       |
|         | 4708.0130    | 3.1680         | 0.070  | 19.50 -6.62                   | 20.79 -6.52                   | SLS       |
|         | 4718.4200    | 3.1950         | 0.240  | 29.00 -6.57                   | 30.42 -6.46                   | SLS       |
|         | 4752.0870    | 4.1860         | 0.440  | 16.68 -6.24                   | 16.68 -6.24                   | MFW       |
|         | 4756.1120    | 3.1040         | 0.090  | 34.43 -6.31                   | 34.43 -6.31                   | MFW       |
|         | 4789.3350    | 2.5440         | -0.330 | 28.78 -6.42                   | 28.78 -6.42                   | SLS       |
|         | 4922.2650    | 3.1040         | 0.380  | 49.08 -6.37                   | 49.08 -6.37                   | SLS       |
|         | 4936.3360    | 3.1130         | -0.250 | 11.50 -6.61                   | 16.30 -6.37                   | SLS       |
| Average |              |                |        | -7.25 ±0.08 (13)              | -7.09 ±0.05 (20)              |           |
| Cr ii   | 5206.0370    | 0.9410         | 0.020  | 140.00 -6.31                  | 140.00 -6.31                  | SLS       |
|         | 5247.5650    | 0.9610         | -1.590 | 26.00 -6.46                   | 26.00 -6.46                   | SLS       |
|         | 5296.6910    | 0.9830         | -1.360 | 32.78 -6.55                   | 32.78 -6.55                   | SLS       |
|         | 5297.3770    | 2.9000         | 0.167  | 40.75 -6.48                   | 40.75 -6.48                   | MFW       |
|         | 5348.3150    | 1.0040         | -1.210 | 38.04 -6.59                   | 38.04 -6.59                   | SLS       |
|         | 5409.7840    | 1.0300         | -0.670 | 84.09 -6.46                   | 84.09 -6.46                   | SLS       |
|         | 5783.0630    | 3.3230         | -0.300 | 4.51 -6.59                    | 4.51 -6.59                    | MFW       |
|         | 5787.9180    | 3.3220         | -0.083 | 19.30 -6.32                   | 19.30 -6.32                   | MFW       |
|         | 6925.2720    | 3.4490         | -0.330 | 5.82 -6.56                    | 5.82 -6.56                    | MFW       |
|         | 6978.3970    | 3.4640         | 0.142  | 18.87 -6.47                   | 18.87 -6.47                   | MFW       |
|         | 6979.7950    | 3.4640         | -0.410 | 6.42 -6.43                    | 6.42 -6.43                    | MFW       |
| Element | Wavelength (Å) | $\chi_{\text{exc}}$/eV | $\log gf$ | EQW abundance HD 37594 (mÅ, dex) | EQW abundance HD 32115 (mÅ, dex) | Ref $\log gf$ |
|---------|---------------|-----------------|-----------|---------------------------------|---------------------------------|-------------|
|         |               |                 |           |                                 |                                 |             |
| Fei     | 4168.9416     | 3.4170          | -1.650    |                                 |                                 |             |
|         | 4189.5550     | 3.6940          | -1.330    |                                 |                                 |             |
|         | 4213.6474     | 2.8450          | -1.290    | 55.70 -5.01                     | 71.11 -4.69                     | FMW         |
|         | 4233.6020     | 2.4820          | -0.604    |                                 | 139.12 -4.57                    | FMW         |
|         | 4248.2240     | 3.0710          | -1.286    | 48.90 -4.94                     | 61.29 -4.67                     | BWL         |
|         | 4250.1180     | 2.4690          | -0.405    | 146.00 -4.79                    | 156.31 -4.58                    | FMW         |
|         | 4626.9640     | 2.7270          | -1.812    | 36.67 -4.87                     | 49.96 -4.57                     | BWL         |
|         | 4627.8260     | 3.1110          | -1.174    | 56.61 -4.91                     |                                 | BWL         |
|         | 4433.2170     | 3.6540          | -0.700    | 58.90 -4.95                     | 80.53 -4.58                     | FMW         |
|         | 4484.2190     | 3.6020          | -0.864    | 64.40 -4.75                     |                                 | BWL         |
|         | 4485.6750     | 3.6860          | -1.020    | 35.83 -4.95                     | 50.21 -4.65                     | FMW         |
|         | 4602.0000     | 1.6080          | -3.154    | 16.70 -4.86                     | 21.98 -4.61                     | FMW         |
|         | 4602.9410     | 1.4850          | -2.209    | 73.70 -4.94                     | 87.52 -4.63                     | BWL         |
|         | 4630.1200     | 2.2790          | -2.587    | 18.00 -4.86                     | 24.27 -4.61                     | BWL         |
|         | 4635.8460     | 2.8450          | -2.358    | 15.50 -4.63                     |                                 | BWL         |
|         | 4643.4630     | 3.6540          | -1.147    | 32.90 -4.90                     | 41.41 -4.68                     | BWL         |
|         | 4683.5597     | 2.8310          | -2.319    |                                 | 15.29 -4.69                     | BWL         |
|         | 4690.1360     | 3.6860          | -1.645    | 14.00 -4.83                     |                                 | BWL         |
|         | 4733.5910     | 1.4850          | -2.988    | 35.18 -4.62                     |                                 | BWL         |
|         | 4736.7720     | 3.2110          | -0.752    | 85.92 -4.90                     | 94.90 -4.64                     | BWL         |
|         | 4745.8000     | 3.6540          | -1.270    | 27.93 -4.88                     | 39.58 -4.59                     | BWL         |
|         | 4789.6508     | 3.5460          | -0.958    |                                 | 58.77 -4.70                     | BWL         |
|         | 4962.5719     | 4.1780          | -1.182    | 17.00 -4.90                     | 24.49 -4.57                     | BWL         |
|         | 4966.0870     | 3.3320          | -0.871    | 70.10 -4.90                     | 92.31 -4.48                     | BWL         |
|         | 4994.1290     | 0.9150          | -3.080    | 48.70 -4.94                     | 55.75 -4.69                     | FMW         |
|         | 5014.9410     | 3.9430          | -0.303    | 76.40 -4.93                     | 87.60 -4.64                     | BWL         |
|         | 5044.2100     | 2.8510          | -2.038    | 18.70 -4.96                     | 28.09 -4.66                     | BWL,BK      |
|         | 5049.8190     | 2.2790          | -1.355    | 84.50 -5.03                     | 102.0 -4.66                     | BWL         |
|         | 5054.6420     | 3.6400          | -1.921    | 5.00 -5.09                      | 10.0 -4.69                      | BWL         |
|         | 5083.3380     | 0.9580          | -2.958    | 48.20 -4.99                     | 62.86 -4.68                     | FMW         |
|         | 5090.7670     | 4.2560          | -0.400    | 46.49 -4.99                     | 63.00 -4.69                     | FMW         |
|         | 5127.3580     | 0.9150          | -3.307    |                                 | 41.22 -4.68                     | FMW         |
|         | 5151.9100     | 1.0110          | -3.322    | 30.70 -4.95                     | 40.87 -4.59                     | FMW         |
Table 4: continued.

| Element | Wavelength Å | \( \chi^{\text{excit}} \) eV | log \( gf \) | HD 37594 EQW abundance mA dex | HD 32115 EQW abundance mA dex | Ref log \( gf \) |
|---------|--------------|----------------|----------|-----------------------------|-----------------------------|------------------|
| 5194.9410 | 1.5570 | -2.090 | 71.06 | -5.01 | 89.29 | -4.70 | FMW |
| 5198.7110 | 2.2230 | -2.135 | 35.30 | -5.02 | 50.82 | -4.68 | FMW |
| 5232.9390 | 2.9400 | -0.058 | 158.60 | -4.85 | 149.16 | -4.76 | BWL |
| 5236.2020 | 4.1860 | -1.497 | 5.00 | -5.09 | 8.38 | -4.79 | BWL |
| 5242.4910 | 3.6340 | -0.967 | 50.40 | -4.83 | 55.67 | -4.68 | BWL |
| 5269.5370 | 0.8590 | -1.321 | 167.67 | -4.86 | 178.64 | -4.56 | FMW |
| 5281.7900 | 3.0380 | -0.834 | 80.31 | -5.03 | 96.56 | -4.70 | BWL |
| 5283.6210 | 3.2410 | -0.432 | 111.91 | -4.71 | 114.97 | -4.72 | BKK |
| 5288.5247 | 3.6940 | -1.308 | 16.30 | -4.91 | 23.18 | -4.65 | BWL |
| 5324.1780 | 2.1100 | -0.103 | 125.00 | -4.96 | 137.90 | -4.72 | FMW |
| 5364.8580 | 4.4450 | 0.228 | 83.60 | -4.96 | 101.52 | -4.66 | BWL |
| 5373.6980 | 3.9400 | -1.514 | 158.60 | -4.85 | 149.16 | -4.76 | BWL |
| 5386.3330 | 4.1540 | -1.770 | 7.16 | -4.77 | 8.38 | -4.79 | BWL |
| 5398.2770 | 4.4450 | -0.670 | 33.60 | -4.78 | 44.39 | -4.54 | FMW |
| 5415.1920 | 4.3860 | -1.508 | 16.30 | -4.91 | 23.18 | -4.65 | BWL |
| 5434.5230 | 1.0110 | -2.122 | 103.70 | -5.02 | 114.97 | -4.72 | FMW |
| 5479.0290 | 4.1540 | -0.760 | 38.99 | -4.88 | 48.57 | -4.60 | FMW |
| 5497.5160 | 1.0110 | -2.849 | 68.04 | -4.81 | 69.43 | -4.66 | FMW |
| 5522.4460 | 4.2090 | -1.550 | 9.10 | -4.75 | 13.71 | -4.49 | FMW |
| 5576.0888 | 3.4300 | -1.000 | 61.30 | -4.82 | 75.26 | -4.55 | FMW |
| 5618.6310 | 4.2090 | -1.276 | 11.40 | -4.92 | 19.03 | -4.60 | BWL |
| 5633.9460 | 4.9910 | -0.270 | 22.30 | -4.79 | 33.26 | -4.51 | FMW |
| 5638.2620 | 4.2200 | -0.870 | 34.02 | -4.75 | 44.39 | -4.54 | FMW |
| 5662.5160 | 4.1780 | -0.573 | 63.83 | -4.56 | 67.53 | -4.46 | FMW |
| 5679.0229 | 4.6520 | -0.920 | 20.20 | -4.65 | 29.83 | -4.38 | FMW |
| 5701.5440 | 2.5590 | -2.216 | 31.85 | -4.66 | 34.71 | -4.56 | FMW |
| 5753.1210 | 4.2600 | -0.688 | 46.33 | -4.63 | 49.56 | -4.53 | FMW |
| 5816.3610 | 4.2090 | -1.276 | 11.40 | -4.92 | 19.03 | -4.60 | BWL |
| 5852.2170 | 4.5480 | -0.601 | 29.12 | -4.93 | 39.12 | -4.62 | FMW |
| 5905.6710 | 4.9910 | -0.270 | 22.30 | -4.79 | 33.26 | -4.51 | FMW |
| 6065.4820 | 2.6080 | -1.530 | 60.60 | -4.96 | 75.56 | -4.67 | FMW |
| 6127.9870 | 4.1430 | -1.399 | 8.70 | -4.99 | 16.49 | -4.61 | BKL |
| 6136.6510 | 2.4530 | -1.400 | 86.11 | -4.98 | 91.65 | -4.69 | FMW |
| 6136.9930 | 2.1980 | -2.950 | 16.30 | -4.91 | 23.18 | -4.65 | BKL |
| 6179.0229 | 4.6500 | -0.920 | 20.20 | -4.65 | 29.83 | -4.38 | FMW |
| 6219.2790 | 2.1980 | -2.433 | 28.82 | -4.89 | 37.39 | -4.64 | FMW |
| 6230.2220 | 2.5590 | -1.281 | 83.77 | -4.93 | 96.11 | -4.66 | FMW |
| 6246.3170 | 3.6020 | -0.733 | 58.95 | -5.00 | 68.34 | -4.79 | BKK |
| 6252.5540 | 4.0400 | -1.687 | 60.75 | -4.97 | 76.18 | -4.67 | FMW |
| 6325.1310 | 2.1760 | -3.299 | 6.51 | -4.68 | 6.51 | -4.68 | FMW |
| 6335.3280 | 4.1430 | -1.474 | 10.50 | -4.82 | 14.46 | -4.60 | BKL |
| 6365.8230 | 3.6860 | -0.856 | 50.37 | -4.93 | 60.57 | -4.72 | BKL |
| 6411.6470 | 3.6540 | -0.595 | 65.13 | -5.01 | 78.87 | -4.62 | BKK |
| 6419.9420 | 4.7330 | -0.240 | 44.53 | -4.83 | 56.25 | -4.61 | FMW |
| 6421.3490 | 2.2790 | -2.027 | 54.10 | -4.83 | 63.30 | -4.61 | FMW |
| 6430.8440 | 2.1760 | -2.006 | 56.24 | -4.91 | 62.60 | -4.73 | FMW |
| 6496.4660 | 4.7950 | -0.570 | 33.86 | -4.56 | 33.86 | -4.56 | FMW |
| Element | Wavelength (Å) | $\chi^{\text{excit}}$ (eV) | log $g_f$ | HD 37594 EQW abundance (mÅ, dex) | HD 32115 EQW abundance (mÅ, dex) | Ref log $g_f$ |
|---------|----------------|-----------------|---------|---------------------------------|---------------------------------|--------------|
|         |                |                 |         | [EQW abundance, HD 37594] | [EQW abundance, HD 32115] |             |
| Fe ii   | 4731.4530      | 2.8910          | -3.000  | [138.9, -4.80]                | [146.7, -4.53]                  | T83av        |
|         | 4993.3430      | 2.8070          | -3.640  | [50.0, -4.83]                 | [52.0, -4.66]                   | T83av        |
|         | 5325.5350      | 3.2210          | -1.320  | [66.6, -4.82]                 | [82.6, -4.52]                   | BSScor       |
|         | 5425.2570      | 3.1990          | -3.160  | [24.3, -4.96]                 | [48.6, -4.55]                   | T83av        |
|         | 5525.1250      | 3.2670          | -3.950  | [16.4, -4.68]                 | [16.4, -4.68]                   | HLGN         |
|         | 5534.8470      | 3.2450          | -2.730  | [82.53, -4.88]                | [101.58, -4.56]                 | BSScor       |
|         | 5591.3680      | 3.2670          | -4.590  | [2.8, 4.98]                   | [5.71, -4.55]                   | RU           |
|         | 5627.4970      | 3.3870          | -4.130  | [13.0, -4.70]                 | [15.0, -4.54]                   | T83av        |
|         | 6084.1110      | 3.1990          | -3.780  | [21.80, -4.85]                | [31.07, -4.59]                  | BSScor       |
|         | 6113.3220      | 3.2210          | -4.110  | [13.7, -4.79]                 | [19.0, -4.57]                   | BSScor       |
|         | 6149.2580      | 3.8890          | -2.720  | [51.68, -4.82]                | [67.0, -4.57]                   | BSScor       |
|         | 6247.5570      | 3.8920          | -2.310  | [89.16, -4.82]                | [106.52, -4.57]                 | BSScor       |
|         | 6369.4620      | 2.8910          | -4.160  | [20.58, -4.80]                | [25.30, -4.63]                  | BSScor       |
|         | 6383.7220      | 5.5530          | -2.210  | [13.74, -4.80]                | [19.23, -4.62]                  | M            |
|         | 6416.9190      | 3.8920          | -2.790  | [50.76, -4.85]                | [63.6, -4.60]                   | M            |
|         | 6432.6800      | 2.8910          | -3.520  | [48.0, -4.88]                 |                                 |              |
|         | 6456.3830      | 3.9030          | -2.100  |                                 | [120.0, -4.49]                  | BSScor       |
|         | 7224.4870      | 3.8890          | -3.240  | [25.60, -4.72]                | [37.85, -4.55]                  | T83av        |
|         | 7449.3350      | 3.8890          | -3.090  | [21.6, 5.05]                  | [32.22, -4.74]                  | HLGN         |
|         | 7479.6930      | 3.8920          | -3.680  | [8.92, 4.85]                  | [14.04, -4.60]                  | BSScor       |
|         | 7515.8310      | 3.9030          | -3.460  |                                 | [26.44, -4.54]                  | T83av        |
|         | 7711.7230      | 3.9030          | -2.500  | [62.34, -4.90]                |                                 | T83av        |
| Average |                |                 |         | -4.84±0.10 (32)               | -4.59±0.08 (35)                  |              |
The accuracy of stellar atmospheric parameter determinations: a case study with HD 32115 and HD 37594

BGHR - Baschek et al. (1970);
BHN - Bizzari et al. (1993);
BK - Bard & Kock (1994);
BKK - Bard et al. (1991);
BSScor - Blackwell et al. (1980);
BWL - O'Brien et al. (1991);
FMW - Fuhr et al. (1988);
HLGN - Hannaford et al. (1992);
K10 - http://kurucz.harvard.edu/atoms.html;
KK - Kroll & Kock (1987);
M - Moity (1983);
MFW - Martin et al. (1988);
PTP - Pickering et al. (2001);
RHL - Ryabchikova et al. (1994);
RU - Raassen & Uylings (1998);
S - Smith (1988);
SLS - Sobeck (2007);
Sm - Smith (1981);
SN - Smith & O'Neil (1975);
SR - Smith & Raggett (1981);
T83av - Ryabchikova et al. (1999);
TB - Seaton et al. (1994)

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