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Accuracy of Laboratory Oscillator Strengths of Ti II Lines as Checked Using High–Quality Stellar Spectra

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Abstract. The accuracy of the laboratory oscillation strengths for Ti II lines measured in the Imperial College London are checked in the wavelength range of 3300–5500 Å using high–resolution high signal–to–noise ratio spectra of three stars with accurate atmospheric parameters: the Sun, Procyon and HD 133792. In total 123 lines are synthesized. About 75 % of the laboratory oscillator strengths correspond to the declared accuracy. Based on the analysis a list of the lines recommended for accurate abundance determinations is created for inclusion in Vienna Atomic Line Database (VALD).

Key words: stars – stellar spectroscopy – abundance analysis – oscillator strengths

1 Introduction

Usually, for accurate abundance determinations one uses the oscillator strengths determined via laboratory measurements, as the theoretical calculations of these quantities are rather inaccurate in most cases. The Spectroscopic Laboratory of the Imperial College in London performs wavelength and transition probability measurements of spectral lines for different atomic species. In particular, the oscillator strengths have been measured for the Ti II lines (Pickering et al., 2001). These data are the potential source for any atomic line database owing to the high accuracy of measurements. However, the VALD group (Vienna Atomic Line Database) has found that not all the measurements correspond to the declared accuracy (Ryabchikova et al., 2008). In this regards, the following task was formulated: to check the accuracy of experimental measurements of oscillator strengths for the lines of Ti II, comparing the observations to the synthetic spectra calculated for stars with known parameters of model atmospheres. For this purpose we used high–resolution, high signal–to–noise (S/N) spectra of Sun, Procyon and Ap star HD 133792.

Why is it necessary to take stars with well–known model atmospheres? The matter is that the line absorption depends on the atmospheric structure. The selective absorption coefficient calculated per 1 gramme is defined by the expression:

$$\sigma = \alpha \frac{n_i}{\rho} \tag{1}$$

where α is the line absorption coefficient (cross–section) per 1 atom, n_i is the number of considered ions in the i–th excitation state, and ρ is density.

Absorption coefficient α is proportional to the oscillator strength of the transition f_{ik}, while the fraction of the absorbing atoms/ions is defined by the temperature and electron density. In the local thermodynamic approximation which is valid in deeper parts of stellar atmospheres n_i is connected to the total number of atoms n_{el} of a given element (atmospheric element abundance) through the Saha–Boltzmann equations. ρ is proportional to the total number of all atoms n_{tot}, therefore we derive that the observed line profile which is defined by the selective absorption coefficient integrated over stellar atmosphere may be expressed as:

$$\sigma =\sim f_{ik} \frac{n_{el}}{n_{tot}} F(p_e, T) \tag{2}$$

where $F(p_e, T)$ is a function of temperature and electron density, $\frac{n_{el}}{n_{tot}}$ is element abundance relative to the total number of atoms, and f_{ik} is the line oscillator strength.

Thus, if the model atmosphere (temperature, pressure and density distribution with the optical depth) and the element abundance are accurately known, we can judge about the accuracy of line oscillator strength by fitting the observed line profile to a synthetic spectrum.

In our work we check not only the latest laboratory measurements by Pickering et al. (2001), but also the earlier measurements for a much smaller number of lines (Bizzarri et al., 1993). On the basis of our analysis we created a recommended list of Ti II lines, which will be included in the VALD with the highest priority.

2 Observations

For the spectral analysis the following observational data has been used: the NSO solar flux atlas (spectral resolution R=550000, (Kurucz et al., 1984)), the flux spectra of Procyon and HD 133392 (a sharp–lined Ap star with a very small magnetic field), obtained with the UVES spectrograph attached on the 8–meter telescope of the European Southern Observatory. The spectral resolution R=80000, S/N≈500 (Procyon) and ≈300 (HD 133792). The spectrum of HD 133792 was obtained in the program 68.D–0254. The Procyon spectrum is taken from the ESO archive. Details of reduction are given in Kochukhov et al. (2006) and in Ryabchikova et al. (2008).

3 Method of Analysis

The analysis consisted in synthetic spectrum calculations in the region of the investigated Ti II spectral lines. The calculations were performed with the Synth3 code, originally written by Piskunov (1992) and essentially modified by O. Kochukhov (Kochukhov, 2007). For all but Ti II spectral lines the atomic parameters were taken from the VALD database (Kupka et al., 1999). Further, using the Binmag2 program, written in language of interactive programming IDL by O. Kochukhov (see http://www.astro.uu.se/∼oleg/download.html), we compared the synthetic spectrum to the observed one. Only unblended lines or lines with the negligible blending (checked with VALD data) have been chosen. For these Ti II lines we fit the observed line profiles changing when necessary the oscillator strength values.

For synthetic spectrum calculations the following models of atmospheres and titanium abundances were used:

The Sun: the effective temperature $T_{\rm eff}$= 5777 K, surface gravity $\log g$= 4.44, rotational velocity $v_{\rm e} \sin i$= 1.9 km s^{-1}, macroturbulent velocity= 3.7 km s^{-1} (value varied from 3.3 to 4 km s^{-1}), microturbulent velocity= 0.9 km s^{-1}. The model is calculated with the ATLAS9 program by Kurucz (Heiter et al., 2002). The solar titanium abundance in a logarithmic scale relative to the total number of atoms is adopted as $\log({\rm Ti}/N_{\rm tot}) = -7.05$.

Procyon: effective temperature $T_{\rm eff}$= 6510 K, surface gravity $\log g$= 3.96 (Allende Prieto et al., 2002), rotational velocity $v_{\rm e} \sin i$= 2.0 km s^{-1}, macroturbulent velocity= 7.0 km s^{-1}, microturbulent velocity= 1.8 km s^{-1}. We used the model calculated by Kurucz and taken from his site

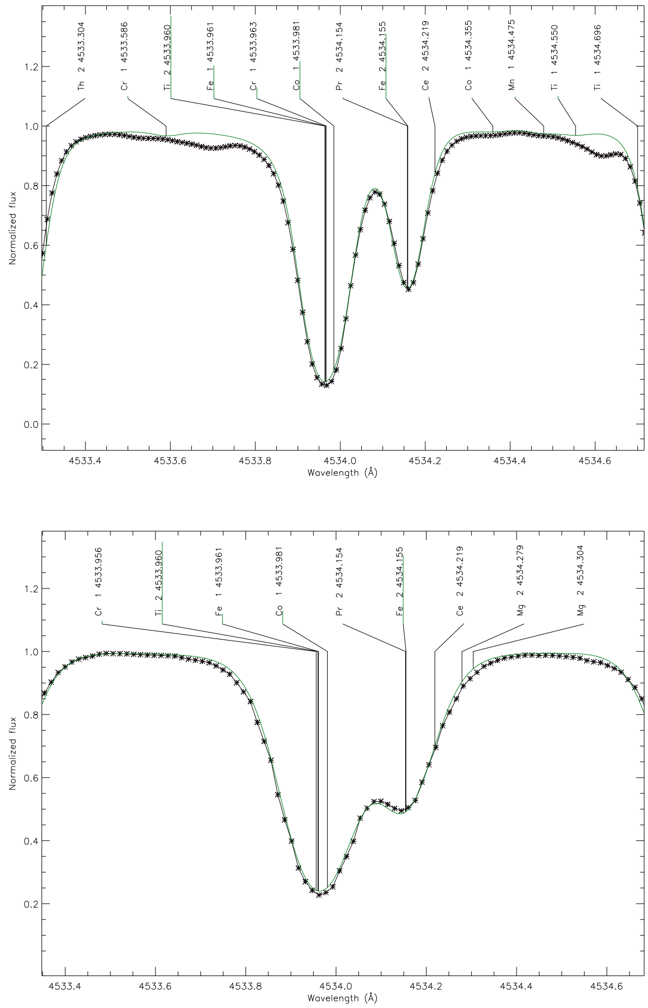

Figure 1: Comparison between the observed (black line with dots) and calculated Ti II 4533.8 Å line in the Sun (left panel) and Procyon (right panel) spectra. The IC value for oscillator strength, $\log(gf) = -0.53 \pm 0.02$ dex, is used.

(http://cfaku5.cfa.harvard.edu/stars.html). The adopted titanium abundance is $\log(\mathrm{Ti}/N_{\mathrm{tot}}) = -7.05$.

HD 133792: effective temperature $T_{\mathrm{eff}} = 9400$ K, surface gravity $\log g = 3.7$, rotational velocity= 1.5 km s^{-1}, zero macroturbulent and microturbulent velocities (Kochukhov et al., 2006). The adopted titanium abundance is $\log(\mathrm{Ti}/N_{\mathrm{tot}}) = -6.88$.

We perform the analysis of Ti II lines in the 3300–5500 Å spectral region. Pickering et al. (2001) presented experimental data for 386 spectral lines in this region with 266 lines having an estimated accuracy. For other lines the upper limits of oscillator strengths are given. Bizzarri et al. (1993) presented laboratory data with the estimated accuracy for 63 Ti II lines in the 3300–5500 Å region. We could check the oscillator strengths for 123 Ti II lines. It includes 100 lines with the estimated accuracy and 23 lines with the upper limits from the IC data and 35 Ti II lines from Bizzarri et al. (1993) data. Ten lines with the upper limits for oscillator strengths in the IC have an estimated accuracy in Bizzarri et al. Most part of the oscillator strengths measured in the IC (91 lines) corresponds to the claimed accuracy of the measurements within $\pm 2\sigma$ (see an example in Fig. 1).

There are 18 lines for which the difference between the IC laboratory oscillator strengths and those needed to fit stellar line profiles is ~ 0.2 dex (50 %), while the claimed accuracy is 12–15 %.

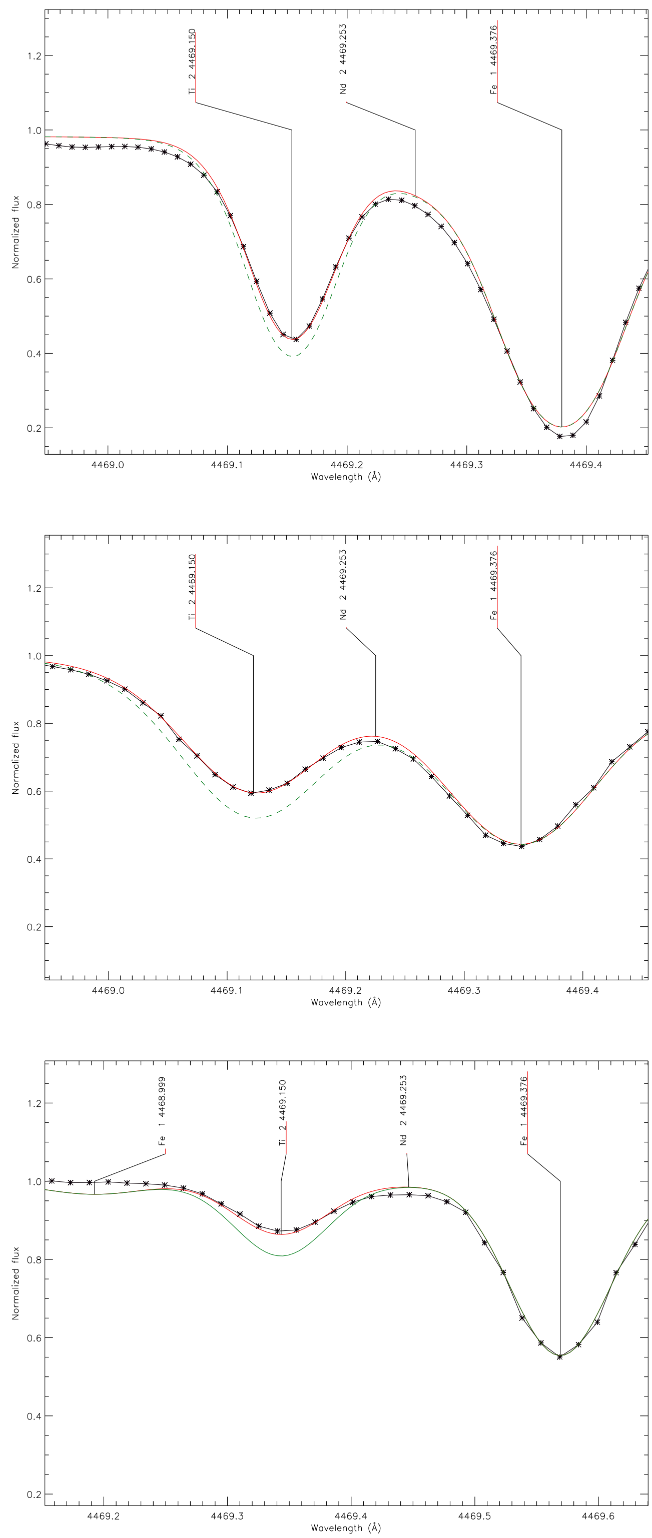

Figure 2: Ti II 4469.15 Å. Black line with asterisks — observed spectrum, dashed green line — synthetic spectrum calculated with IC $\log(gf) = -2.33 \pm 0.05$ dex, full red line — best fit to the observations with $\log(gf) = -2.48$ (Sun — left panel), $\log(gf) = -2.57$ (Procyon — middle panel), $\log(gf) = -2.52$ (HD 133792 — right panel).

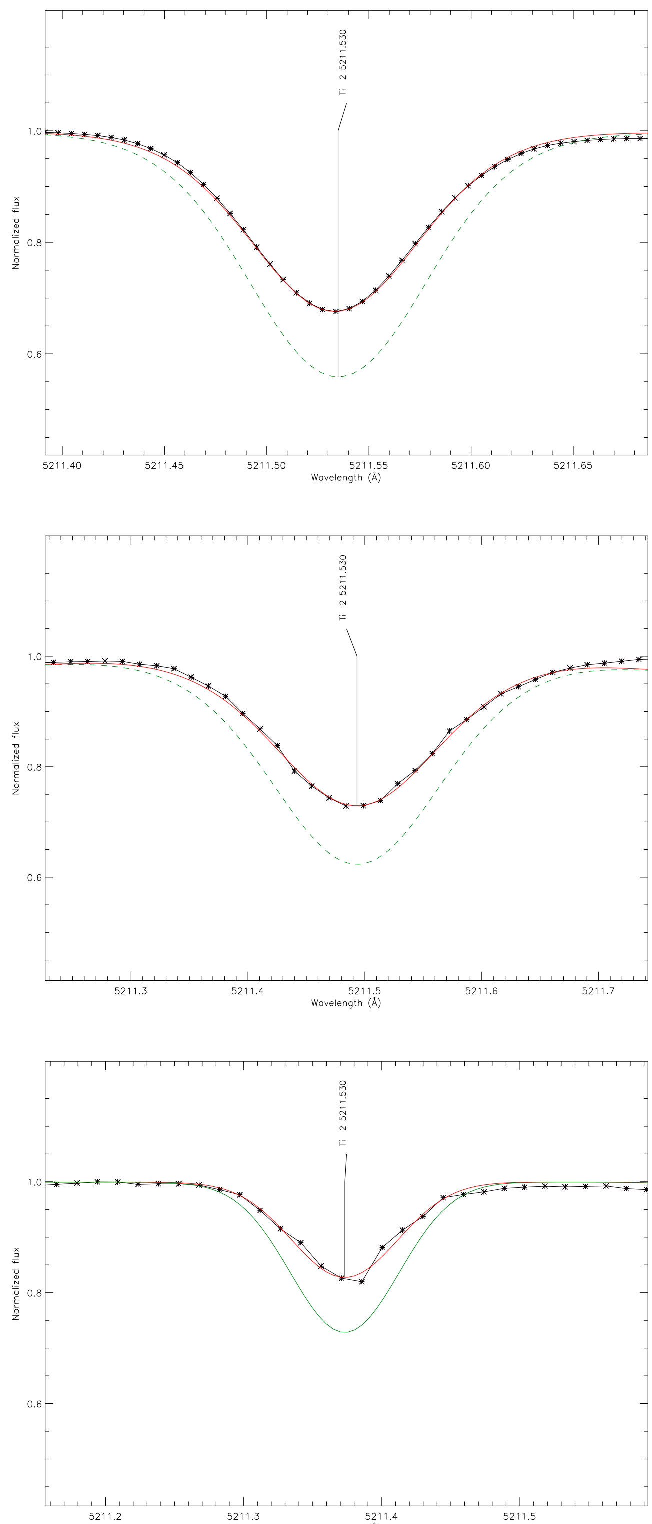

Figure 3: Ti II 5211.53 Å. Black line with asterisks — observed spectrum, dashed green line — synthetic spectrum calculated with IC $\log(gf) = -1.16 \pm 0.05$, full red line — best fit to the observations with $\log(gf) = -1.54$ (Sun), $\log(gf) = -1.55$ (Procyon) and $\log(gf) = -1.45$ (HD 133792).

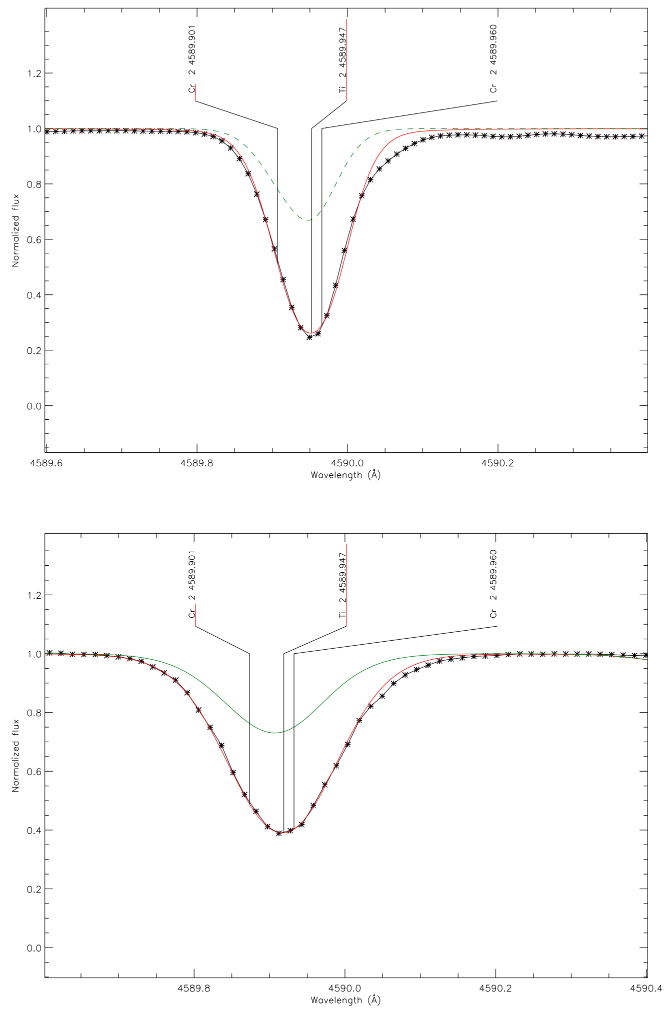

Figure 4: Ti II 4589.947 Å. Black line with asterisks — observed spectrum, dashed green line — synthetic spectrum calculated with IC $\log(gf) = -2.94$, full red line — best fit to the observations with $\log(gf) = -1.54$ (Sun) and $\log(gf) = -1.55$ (Procyon).

For 4 lines Bizzarri et al. (1993) data provide a good fit. An example of such a case is shown in Fig. 2.

Finally, for 14 lines the IC laboratory data strongly deviate from those needed to fit the observed spectra. The first example is shown in Fig. 3 for Ti II $\lambda\,5211.53$ Å. The laboratory value is $\log(gf) = -1.16 \pm 0.05$, while to fit the line profile in the stellar spectra one needs to decrease the oscillator strength by 0.3–0.4. The second example is shown in Fig. 4. The laboratory oscillator strength for the Ti II 4589.947 Å line is underestimated by 1.4 dex. Again, for 4 lines Bizzarri et al. (1993) oscillator strengths provide a reasonable fitting to the observed line profiles in the program stars.

Generally, laboratory oscillator strengths reported by Pickering et al. (2001) and by Bizzarry et al. (1993) agree within the measurement errors, however, in most cases where a difference between two data sets exceeds 2σ, a preference should be given to Bizzarry et al. (1993) data. It is taken into account in creating a recommended list of Ti II lines with accurate laboratory oscillator strengths for the abundance determinations. The final Ti II line list for the accurate abundance analysis in 3300–5500 Å range consists of 99 lines which will be included in the VALD with the highest priority.

Using only the recommended Ti II lines we re–estimated the titanium atmospheric abundance

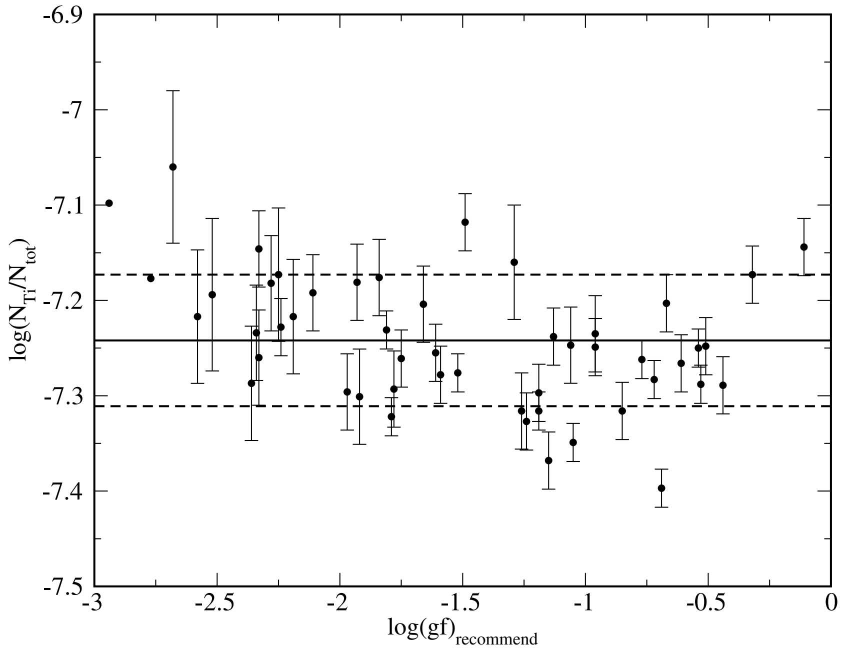

Figure 5: Titanium abundance derived from 50 individual Ti II lines in 21 Peg using recommended lines with laboratory oscillator strengths measurements. Vertical bars indicate error bars in the laboratory measurements. Horizontal lines indicate a standard deviation in abundance determination.

in the Sun and Procyon:

$$\log(\mathrm{Ti}/N_{\mathrm{tot}})^{\mathrm{Sun}} = -7.06 \pm 0.06 \quad (69 \text{ lines}),$$

$$\log(\mathrm{Ti}/N_{\mathrm{tot}})^{\mathrm{Procyon}} = -7.02 \pm 0.08 \quad (69 \text{ lines}).$$

To prove further the accuracy of our recommended lines we used equivalent widths of 50 Ti II lines measured in the spectrum of sharp–lined normal A–type star 21 Peg (Fossati et al., 2009). Using the model atmosphere from this paper and only the recommended oscillator strengths we get:

$$\log(\mathrm{Ti}/N_{\mathrm{tot}}) = -7.24 \pm 0.07.$$

Fig. 5 demonstrates the quality of recommended data.

4 Conclusions

We found that the most part of the Ti II oscillator strengths measured in the Imperial College correspond to the declared accuracy and may be recommended for the accurate abundance analysis in stellar atmospheres. For $\sim 20\,\%$ of investigated lines a difference between laboratory value and that needed to fit the observed line profile exceeds $3\,\sigma$. These values require an additional check before being recommended for the accurate abundance analysis. However, for 14 out of 123 investigated lines the laboratory data strongly deviate from the astrophysical values (examples: 5396.226, 5211.530, 4589.946, 4524.679, where the deviation is typically 0.3–0.6 dex and up to 1.5 dex!). Laboratory oscillator strengths of these Ti II lines cannot be included in the VALD database as recommended for accurate stellar spectrum analysis. A part of them are replaced with the laboratory data from the earliest publication by Bizzarri et al. (1993). The final Ti II line list for the accurate abundance analysis in the 3300–5500 Å range consists of 99 lines which will be included in the VALD with the highest priority.

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