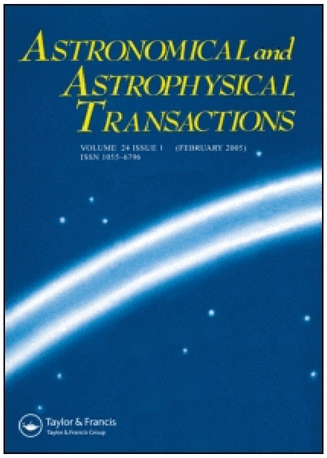

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ON THE EFFECT OF LINE BLANKETING ON THE Fe I LINE INTENSITIES IN THE SOLAR, ARCTURUS AND PROCYON SPECTRA

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The influence of the blanketing effect on the intensities of Fe I lines in solar and stellar atmospheres is investigated. More than 18,000 spectral lines of 14 elements were taken into account. It was demonstrated that ignoring the line-blanketing effect produces an error in the estimation of iron abundance of 0.04 dex in the case of the Sun and solar-type stars. (The iron abundance is given in the logarithmic scale and dex means the decimal logarithm estimation error.)

Keywords: Sun; Stellar atmospheres; Abundances; Lines blanketing

1 INTRODUCTION

Continuum radiation controls the photoionization transitions of many atoms in astrophysical plasma. For this reason, the Saha–Boltzmann local equilibrium ionization formula produces substantial errors in many cases. However, it is very difficult to incorporate continuum radiation in non-local thermodynamic equilibrium (NLTE) calculations because there are millions of spectral lines that decrease the continuum flux: the so-called line-blanketing effect. Few methods have been developed to take the effect into account. In the first NLTE calculations the continuum flux was replaced by the Planck function with an appropriate radiation temperature (see for example Athay and Lites (1972)). Recently Busa *et al.* (2001) proposed to represent the continuum absorption coefficient $k^{\nu}_{\rm LB}$ in the following form:

$$k^{\nu}_{\rm LB} = k^{\nu}_{\rm NLB}\left[1 + \text{constant} \times \ln\left(\frac{F^{\nu}_{\rm NLB}}{F^{\nu}_{\rm LB}}\right)\right], \tag{1}$$

where $k^{\nu}_{\rm NLB}$ is the total opacity coefficient without line blanketing, and $F^{\nu}_{\rm NLB}$ and $F^{\nu}_{\rm LB}$ are continuum fluxes at frequency ν without and with the line blanketing respectively. Busa *et al.* replaced the ratio $\ln(F^{\nu}_{\rm NLB}/F^{\nu}_{\rm LB})$ by an empirical function derived from observed continuum energy distributions of stars with different $T_{\rm eff}$, $\log g$ and metallicities.

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The aim of this paper is to describe results of our NLTE calculations that demonstrate the direct line-blanketing influence (hereafter referred to as the direct method) on the intensities of neutral iron lines for the Sun, Arcturus and Procyon. We have compared our results with the results derived using the approach adopted by Busa *et al.* (2001) (hereafter referred to as the approximate method).

2 THE PROCEDURE OF LINE-BLANKETING MODELLING AND NON-LOCAL THERMODYNAMIC EQUILIBRIUM CALCULATIONS

We calculated directly the value k^{ν}_{LB} in Eq. (1); that is, we did not replace the $\ln(F^{\nu}_{NLB}/F^{\nu}_{LB})$ ratio with the approximation function as Busa *et al.* did. More than 18,000 spectral lines of 14 chemical elements were used to model line blanketing. A number of lines of diatomic

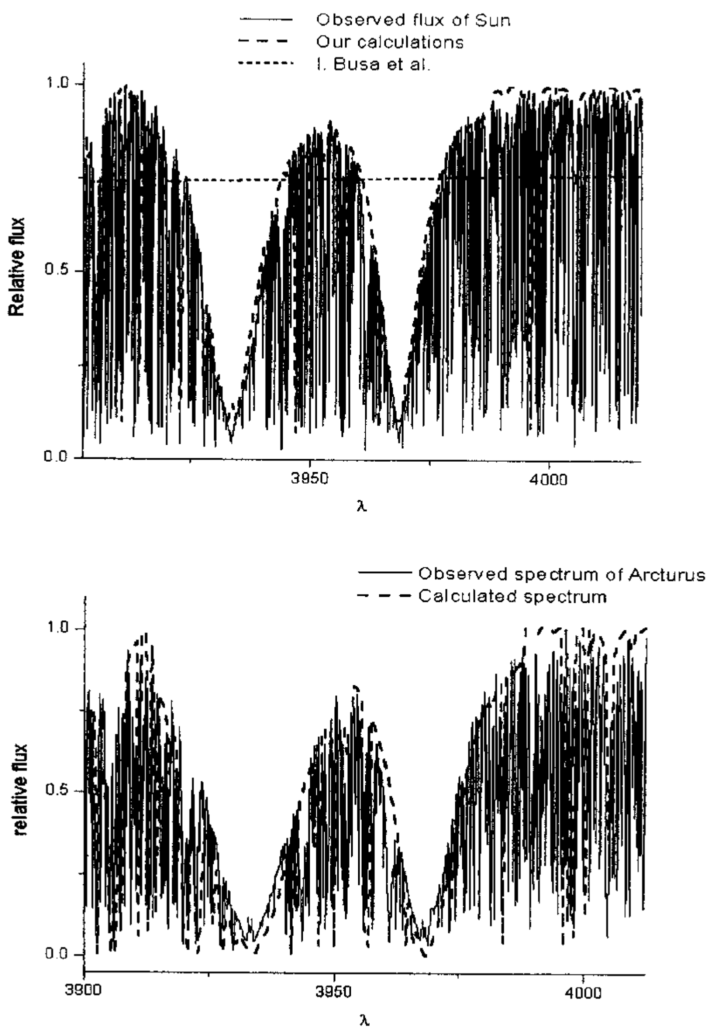

FIGURE 1 Computed and observed spectra of the Sun and Arcturus.

molecules such as CH and CN were included as well. Oscillator strengths, excitation potentials and statistical weights for spectral lines of interest were adopted from Kurucz (1993a), and damping constants from the VALD database (Kupka *et al.*, 1999). The classical approximation was used to estimate radiative and collision damping because of the lack of appropriate parameters in the VALD database.

The populations of the levels of blanketing lines were calculated in the framework of the local thermodynamic equilibrium (LTE) approximation. To model the influence of thousands of spectral lines on the continuum flux we used the ABSLIN procedure of the MULTI code (Carlsson, 1986). Observed and calculated spectra of the Sun and Arcturus are shown in Figure 1 for the spectral band in the vicinity of the H and K Ca II lines.

For the solar spectrum we also plotted a theoretical curve derived by the Busa *et al.* (2001) method. It can be seen that our calculations fit the observed spectrum much better.

We used the MULTI code and stellar atmosphere models of Kurucz (1993b) and a 100-level Fe I atom model was also employed. The model includes 99 Fe I levels and one Fe II level. We have taken into account 506 bound–bound transitions. Finally, more than 4000 transitions were included in our atom model (permitted, forbidden and ionization transitions). Photoionization is the main reason for departure from LTE in the case of Fe I line formation in stellar atmospheres (Athay and Lites, 1972). So the photoionization cross-sections should be sufficiently accurate and we adopted those from the IRON-project calculations (Bautista, 1997).

The following values of $T_{\rm eff}$ $\log g$ and [Fe]/[H] were taken: 5777 K, 4.44 and 0.0 for the Sun; 4290 K, 1.9 and -0.7 for Arcturus; 6500 K, 4.00 and 0.0 for Procyon.

3 THE RESULTS

Equivalent widths (EWs) of 506 Fe I lines were calculated with allowance for continuum blanketing as described in the previous section and using the Busa *et al.* (2001) approximation as well. These values were compared with EWs of iron lines computed for the Sun, Arcturus and Procyon with the non-blanketed continuum. The summary of our results is presented in Table I for each of these stars. The first and second rows of the table contain the numbers of lines that have EWs greater than and less than respectively that in the non-blanketed case by a factor of more than 1.5 for our and the Busa *et al.* (2001) approach (we shall refer to these lines as lines with anomalous weakened and strengthed intensities respectively). The total numbers of lines with anomalous intensities are presented in the third

TABLE I Summary of Our Results.

	Sun		*Procyon*		*Arcturus*	
Parameter	*Direct method*	*Approximate method*	*Direct method*	*Approximate method*	*Direct method*	*Approximate method*
Number of lines (W(nb)/W(b) > 1.5)	47	5	38	0	44	0
Number of lines (W(nb)/W(b) < 0.75)	7	14	0	1	35	41
Number of abnormal lines	54	19	38	1	79	41
Mean W(nb)/W(b)	0.915	0.957	0.965	1.094	0.911	0.992
Abundance correction (dex)	−0.038	−0.019	−0.015	0.039	−0.04	−0.003

row of Table I. The fourth row contains the mean ratios of blanketed continuum intensity to non-blanketed continuum intensity. The anomalous intensity lines were excluded in these ratios. The last row contains the corrections to the iron abundance due to the blanketing effect.

Our calculations indicate that about 10% of Fe I lines are weakened significantly. This occurs because some iron lines are formed in the strong wings of lines of other atoms. For example Fe I (43) ($\lambda = 3969$ Å) line is weakened by up to ten times in the cases of the Sun and Arcturus and by up to 3.5 times for Procyon. (The symbol (43) means that Fe I lines belong to the multiplet number 43). This is explained by the presence of the H Ca II line near the Fe I line ($\lambda = 3969$ Å). The Fe I ($\lambda = 2795.1$ Å) line is blended with the Mg II ultraviolet doublet. As a result the iron line is weakened by 1700 times for Procyon, by 100 times for the Sun and by ten times for Arcturus. The number of strongly weakened lines appears to be much less if we use the approach of Busa *et al.* (2001) in which the continuum flux is approximated with a smooth function almost without depressions produced by absorption lines.

Decreasing continuum intensity due to the blanketing effect results in the increasing EWs of some Fe I lines. The spectrum of Arcturus contains the largest number of such lines. As follows from the second row of Table I, the number of such lines increases with decreasing stellar T_{eff}. All these lines are not strong (in most cases their EWs do not exceed 50 mÅ). The numbers of strengthened iron lines are nearly equal in both the direct and approximate methods. The appearance of strengthened lines is due to obvious NLTE effects. The total number of Fe I anomalous intensity lines is increased from Procyon to Arcturus. Therefore both methods indicate that the role of blanketing increases with decreasing effective temperature.

It follows from Table I that, if the blanketing effect is taken into account in our approach, then the EWs of Fe I lines increase to 10% on average if comparison is made with the results of non-blanketing calculations. The situation is not so clear in the case of the approximation method; Fe I lines are strengthened to 4% for the Sun and to 1% for Arcturus but are weakened to 10% for Arcturus.

Iron abundance corrections are presented in the bottom row of Table I. All of these are negative for the direct method; they are minimal for Procyon and maximal for Arcturus. In the case of the approximate method the abundance corrections are negative for the Sun and Arcturus, but positive for Procyon.

4 CONCLUSIONS

We investigated the effect of line blanketing on the intensities of Fe I lines in the spectra of the Sun, Arcturus and Procyon. More than 18,000 lines of 14 elements were included in our NLTE calculations. It was found that computed and observed spectra of investigated stars are in good agreement. We compared our direct blanketing consideration method with the approximate approach of Busa *et al.* (2001).

We demonstrated that line blanketing changes the theoretical EWs of Fe I lines significantly; the role of this effect increases with decreasing stellar effective temperature.

In our direct method we found that the EWs of most Fe I lines increase if line blanketing is taken into account. We derived the opposite result in some cases to the approximate blanketing method of Busa *et al.* (2001) and concluded that it is necessary to use this method with care.

Uncertainties in the van der Waals damping parameters γ_{vdW} and collisional cross-sections of iron atoms with hydrogen are the main sources of errors in iron abundance determination from NLTE calculations (Bayazitov and Galiev, 1999; Gehren *et al.*, 2001). For instance the increase in γ_{VdW} values by a factor of 2 produces iron abundance corrections of 0.05 dex, and the increase in collisional cross-sections of Fe I with hydrogen by three times produces an error of 0.04 dex. On the other hand it follows from our calculations that neglecting line blanketing produce an error in the iron abundance of up to 0.04 dex for the Sun and cool stars.

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