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# Sensitivity indicators of Fraunhofer lines

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**Abstract.** To estimate the sensitivity of absorption lines to the physical conditions in the solar atmosphere, we propose indicators computed using the depression response functions in the LTE approximation. For 604 Fe I and 58 Fe II, lines the sensitivity indicators of temperature, pressure, and microturbulent velocity, as well as the average geometrical height of formation of the line depression response to changes of temperature are given in graphic and tabular forms[1].

The sensitivity indicators can be used not only for a choice of the specific line, but for the photosphere diagnostics as well. The latter application is possible only for investigations of the temperature when the temperature fluctuations are no more than 8%. Only approximate estimates of the pressure and microturbulent velocity are possible.

**Key words:** Sun: atmosphere – Sun: photosphere

## 1. Introduction

Often, the diagnostics of stellar atmospheres requires lines more sensitive to one atmospheric parameter and less sensitive to others. To execute a correct choice of such lines, we offer to apply sensitivity indicators. The calculation of sensitivity indicators is based on the use of the depression response functions $RF(x, \lambda)$ (Magain 1986). The detailed description of the calculation techniques was already announced in Sheminova (1993, 1995). The response function defines the rate of variation in the line depression $R(x, \lambda) = (I_c(x, \lambda) - I_l(x, \lambda))/I_c(x, \lambda)$ at every point $x$ in the atmosphere relative to the rate of variation of the atmospheric parameter $\beta$, which undergoes the local disturbance $\Delta\beta/\beta$. If we integrate the response function $RF_{R,\beta}(x, \lambda)$ with respect to $x$ and divide it by the value of the emerging depression $R(\lambda)$, we obtain a dimensionless quantity $I_{R,\beta}$, which is a variation in the observed line depression, $\Delta R/R$, relative to the local variation $\Delta\beta/\beta$:

$$I_{R,\beta}(\lambda) = \frac{1}{R(\lambda)} \int_{-\infty}^{\infty} RF_{R,\beta}(x, \lambda) dx.$$

We call it the sensitivity indicator of the line depression.

## 2. Data for calculations

For quantitative evaluation of the line sensitivity, we shall use the indicator, which gives a relative change of the line depression for a 1% change of the atmospheric parameter. The indicator shows how the line absorption (in percentage) has changed, if the atmospheric parameter has increased by 1% in the region of line formation. The sign of the indicator + (-) testifies that the line absorption was increased (reduced). For the description of the spectral line sensitivity, it is enough to use the indicators for the central line depth ($I_{R,\beta}$) and for the equivalent width ($I_{W,\beta}$). The most interesting in the spectral analysis problems is the study of the line sensitivity to the temperature ($T$), the gas pressure ($P_g$ ) and the microturbulent velocity ($V_{mic}$). Therefore, the sensitivity indicators were calculated only for these atmospheric parameters.

Calculations of indicators were performed for 604 absorption lines of Fe I and 58 Fe II lines. The line parameters are listed in the table. The condition of choice of the spectral lines is the absence of blends in the line profiles. In the solar spectrum, there are not enough such lines. To start, the line profiles were simply examined in the Atlas of the solar spectrum (Delbouille et al. 1973). Further, the bisectors of these lines were calculated and compared with an average bisector of the given group of lines. The line groups were chosen for different excitation potentials of the lower level, the central line depths, and the line wavelengths. The list of lines was purposely extended at the expense of lines with weaker blends to receive the maximum of lines suitable (or conditionally suitable) for the analysis of the fine structure of the line profiles and primarily of all for study of the line asymmetries. Partially, this list of lines in the range $\lambda\lambda$ 505.0–665.0 nm was already used by Brandt & Gadun (1993, 1995) for study of changes in the spectral line parameters above the active areas.

The calculations of the sensitivity indicators were performed using the SPANSAT codes (Gadun & Sheminova 1988) in an LTE approximation. For some lines used in this study, NLTE effects may be essential. For example, as is shown in Sheminova & Matveev 1984, the equivalent widths and central depths of Fe I weak lines with low excitation potentials decrease by 10%,

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[1] Tables 1 and 2 are only available in electronic form at the CDS via anonymous ftp to cdsarc.u-strasburg.fr (130.79.128.5) or via http://cdsweb.u-strasbg.fr/Abstract.html

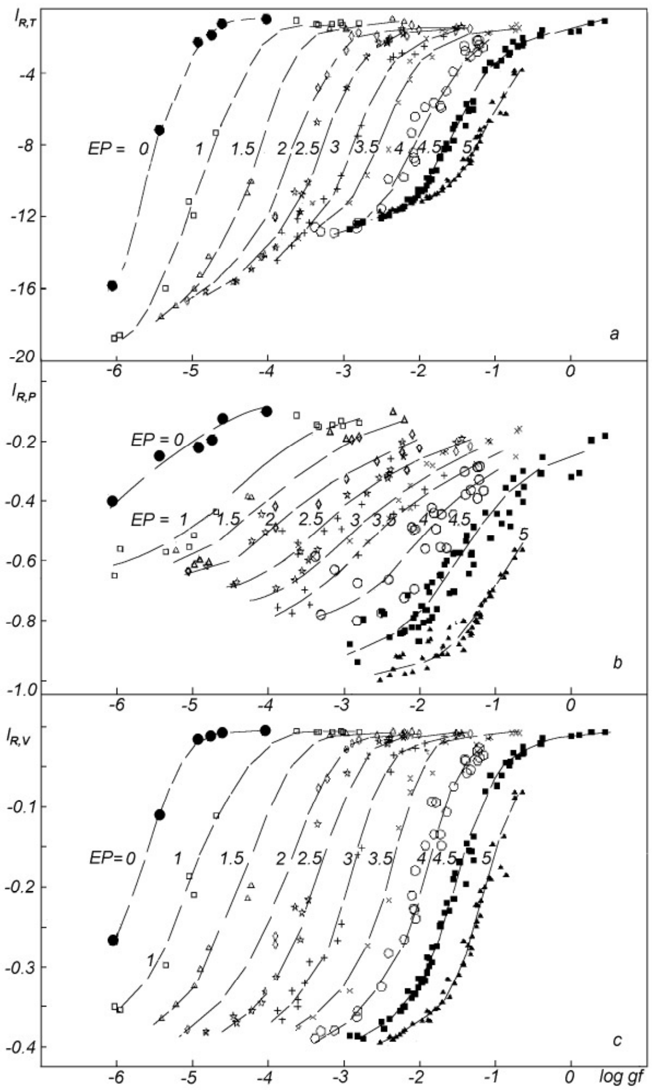


Fig. 1

**Fig. 1a–c.** Indicators of the sensitivity of central depths of Fe I lines depending on the oscillator strengths log $gf$ and lower excitation potentials ($EP$, eV): **a** to the temperature; **b** to the gas pressure; **c** to the microturbulent velocity.

on the average, when deviations from LTE are taken account. In calculations of the sensitivity indicators, we used the HOLMU model atmosphere (Holweger & Müller 1974) with excitation temperature based on observations of the Fe I line profiles. Thus, the probable NLTE effects for Fe I lines are taken into account in an indirect way. The values of micro ($V_{mic}$) and macroturbulent ($V_{mac}$) velocities, which vary with height in the photosphere, were taken from Gurtovenko & Kostyk (1989):

$$V_{mic} = \text{const} = 1.08\text{km/s}, \qquad H \leq 130\text{km};$$

$$V_{mic} = 0.946\text{km/s} + H(1.88 \cdot 10^{-3} - 6.75 \cdot 10^{-6} H)\text{km/s}, \qquad 130\text{km} < H \leq 420\text{km};$$

$$V_{mic} = const = 0.55\text{km/s}, \qquad H > 420\text{km};$$

$$V_{mac} = \text{const} = 1.85\text{km/s}, \qquad H \leq 200\text{km};$$

$$V_{mac} = 2.10\text{km/s} - H(1.55 \cdot 10^{-3} - 1.30 \cdot 10^{-6} H)\text{km/s}, \qquad 200\text{km} < H \leq 675\text{km};$$

$$V_{mac} = \text{const} = 1.65\text{km/s}, \qquad H > 675\text{km}.$$

The Van der Vaals damping constant was taken with the correction factor 1.3. The line oscillator strengths and the solar iron abundance were found by comparison between calculated and observed central line depths.

## 3. Results

In Figs. 1 and 2, we present dependencies on oscillator strengths and lower excitation potential for sensitivity indicators of central depths of iron lines to the temperature, the gas pressure, the microturbulent velocity. Figs. 3 and 4 give the average geometrical heights of localization of the effective response to the temperature variations for central depths and the equivalent widths of these lines. In addition, Figs. 3c, 4c show for central line depths the average formation heights in comparison with heights of effective responses to variations of the temperature, the gas pressure, and the microturbulent velocity. The heights of formation are computed from the contribution function to the line depression (Gurtovenko et al., 1991).

Tables 1 and 2, which are only available in electronic form, present the list of 604 Fe I and 58 Fe II lines using in this paper and data: 1) the atomic line parameters – the wavelength $\lambda$ (nm), the lower excitation potential $EP$ (eV), the oscillator strength log $gf$; 2) the line characteristics – the observed central line depth $R$, the calculated equivalent width $W$ (pm); 3) the sensitivity indicators to the temperature for the central line depths $I_{R,T}$, for the line depths on half-width $I_{0.5R,T}$, and for the equivalent widths $I_{W,T}$; 4) the average geometrical heights of localization of the effective response to the temperature variations for the central line depths, $H_{R,T}$ (km), for the line depths on half-widths, $H_{0.5R,T}$ (km), and for the equivalent widths, $H_{W,T}$ (km).

As can be seen from Figs. 1 and 2, the sensitivity to the temperature is higher (approximately 10 times) than to other atmospheric parameters. Analyzing in detail the sensitivity indicators obtained in the present paper and in the papers of Sheminova (1993, 1995) for iron lines as well as for spectral lines of other atoms, we have established that the most responsive to the temperature are the lines with excitation potentials from 0 to 2 eV, central line depths up to 0.35, and equivalent widths up to 3 pm. Relative variations of equivalent widths ($\Delta W/W$) of these lines are 25-35% when the temperature changes by 2%. Medium-strong lines of light atoms with $EP \geq 6$ eV are highly responsive to the gas pressure. For them, $\Delta W/W$ is as much as 25–48% when $P_g$ changes by 30%. Strong lines of heavy atoms with $W \approx$ 8–12 pm are very sensitive to the microturbulent ve-

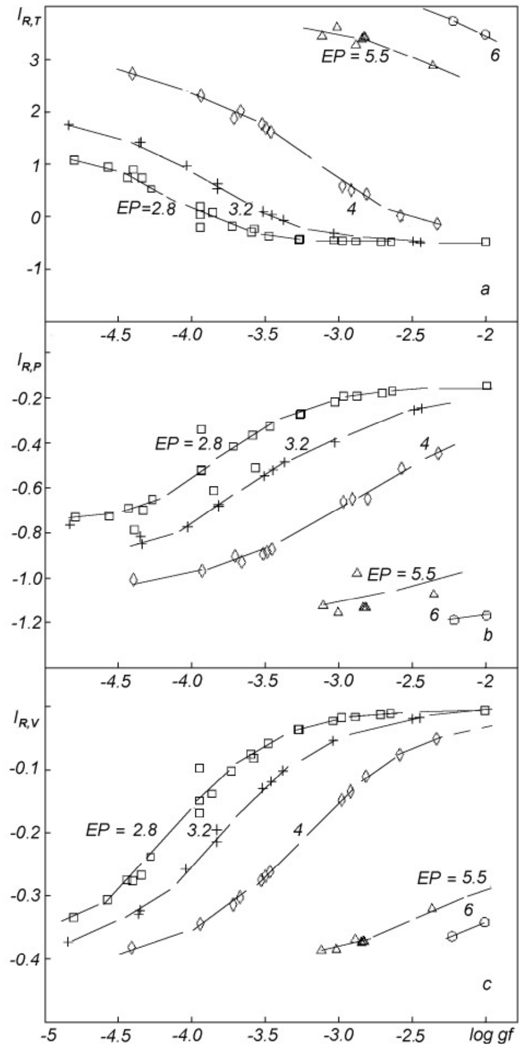


Fig. 2

**Fig. 2a–c.** The same as Fig. 1, but for the Fe II lines.

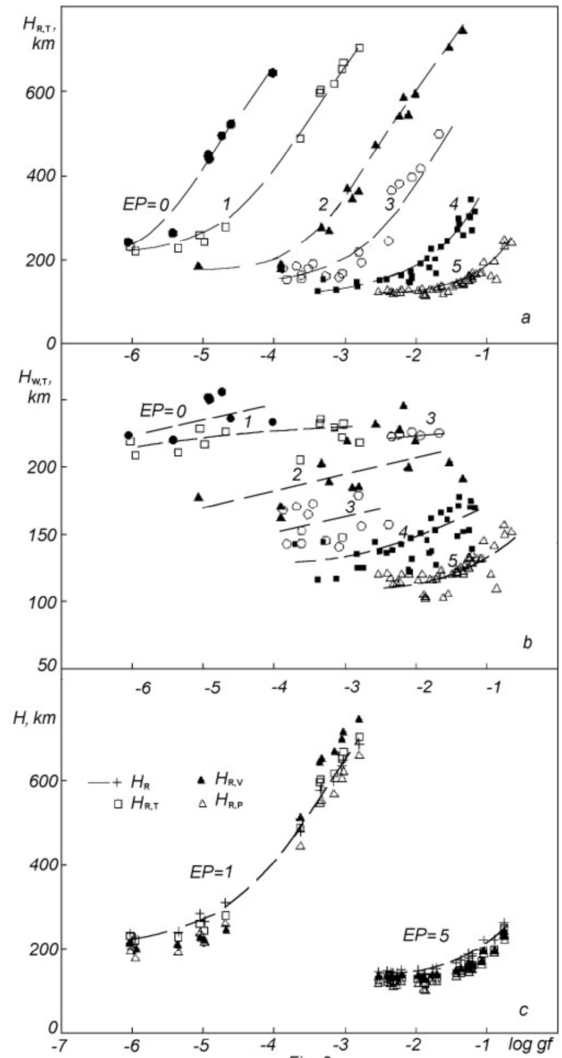


Fig. 3

**Fig. 3a–c.** The heights of effective responses depending on oscillator strengths and excitation potentials: **a** and **b** to the temperature variations for the central depths ($H_{R,T}$) and the equivalent widths($H_{W,T}$) of Fe I, **c** to the temperature ($H_{R,T}$), pressure ($H_{R,P}$), microturbulence variations ($H_{R,V}$) for the central depths of Fe I lines as compared with the average heights of formation of the central depths ($H_R$).

locity. For these lines, $\Delta W/W$ amounts to 11–18% when $V_{mic}$ changes by 50%.

## 4. Application

The sensitivity indicators can be used for temperature diagnostics in the photospheric layers. So, for example, if we want to know the temperature variations $\Delta T/T$ in the region of the perturbed photosphere, we should find a line with high sensitivity to temperature and with low sensitivity to pressure and velocity. For this purpose, we shall use graphic dependencies of the sensitivity indicators to temperature, pressure, and velocity (Figs. 1, 2). We should take into account the real limits in the probable values of the atmospheric parameters fluctuations. Further, for the line chosen we measure a relative difference between observed central depths in the perturbed region and in the quiet region, $\Delta R/R$. In the table, we find the temperature sensitivity indicator ($I_{R,T}$). Finally, we calculate the relative change of temperature $\Delta T/T$ with the help of a simple ratio $\Delta T/T = (\Delta R/R)/I_{R,T}$. The height where this temperature variation occurs in the photosphere corresponds to the height ($H_{R,T}$), where the effective response of the central line depression to this variation takes place. The heights $H_{R,T}$ are shown in Figs. 3 and 4 and Tables 1 and 2.

However, the described application of sensitivity indicators for the temperature diagnostics of the photosphere is not possible in all cases. The accuracy of evaluations of changes of atmospheric parameters in the perturbed photosphere depends on the assumptions accepted when solving equations to obtain the response functions (Caccin et al. 1977). The main assumptions are: 1) LTE, and 2) that the perturbations of atmospheric pa-

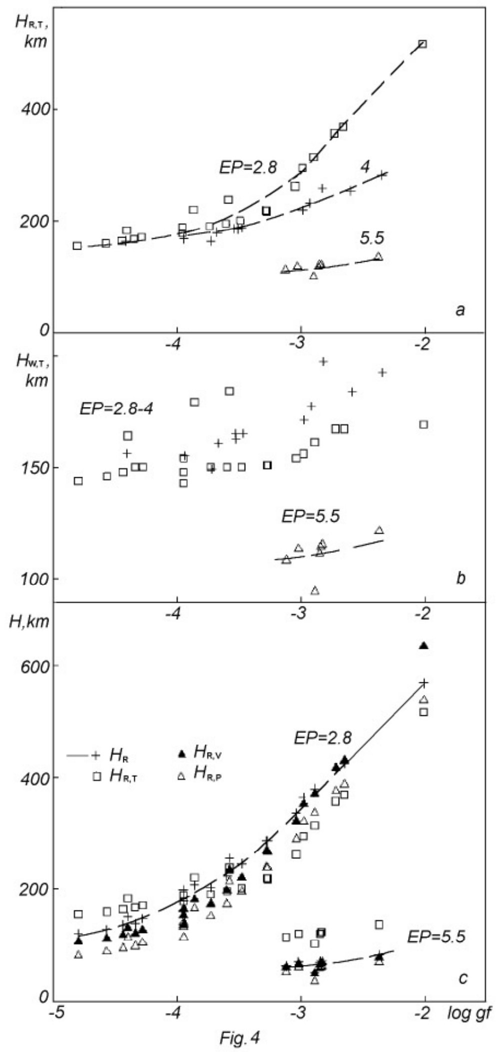


**Fig. 4a–c.** The same as Fig. 3, but for the Fe II lines.

rameters should be small, $\Delta T/T \ll 1$. According to our results (Sheminova 1993), the applications of the sensitivity indicators for the temperature diagnostics of the photosphere are possible when the observed variation in the central line depth $\Delta R$ does not exceed $R/2$, and the disturbance magnitude ($\Delta T/T$) is no more than 8 % ( $\approx$ 400 K).

It must be noted that the sensitivity indicators are less suitable for pressure and microturbulence diagnostics. The sensitivity to the microturbulent velocity is connected with the saturation of strong lines. In this case, the excitation temperature and NLTE effects may influence the accuracy of the estimates of the sensitivity of line profiles to microturbulence. In addition, gradients of temperature fluctuations which are not taken into account in calculations may introduce additional errors, because the temperature sensitivity of lines far exceeds the other ones. Nonetheless, approximate estimates of pressure and microturbulence fluctuations may be obtained when it is considered that the effective widths of the formation regions of central depths of Fe lines used are not too large (75–115 km).

The sensitivity indicators can also be applied to the evaluation of possible errors due to low accuracy of the model atmospheric parameters. So, for example, when determining the abundances of chemical elements, the error in the temperature adopted will cause errors considerably larger than NLTE effects or errors of the velocity and the damping constant. Such evaluations are of great practical importance for the determinations of the abundances of chemical elements in stellar atmospheres, which models are less accurate.

## 5. Conclusion

We may draw the following conclusions from calculations of the sensitivity indicators presented in this paper:

1. The photospheric lines of Fe I are the most responsive to temperature variations. Even minor temperature fluctuations of the order of 1% can be measured with the help of the most responsive lines. The sensitivity to the temperature is higher than to other atmospheric parameters by approximately 10 times.

2. The sensitivity indicators presented on the plots and in the table may be very valuable for fast and easy analysis of the magnitudes of the response of the line depression to the physical conditions in the solar atmosphere. The estimates of the line sensitivity to pressure and microturbulence are less accurate than to the temperature. The temperature sensitivity indicator table computed for individual lines may be useful for the temperature diagnostics in the photospheric layers, and also for choice of the line with the predominant temperature sensitivity or the group of lines with the same temperature sensitivity. The group of this type is often required for more detailed spectral analysis of the solar and stellar atmospheres.

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