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ON THE AVERAGE OPTICAL DEPTHS OF FORMATION OF SOME FRAUNHOFER LINES

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SUMMARY: Average optical depths of the line depression formation in the center of the solar disk for eighteen selected Fraunhofer lines have been calculated for six solar atmosphere models given by Vernazza *et al.*, (1981). Some regularities in the behavior of the average optical depths vs. central residual intensities of the line profiles and lower level excitation potential have been examined.

1. INTRODUCTION

Many depth-dependent solar phenomena such as motions, magnetic field etc., are investigated through the study of Fraunhofer lines. In the attempt to choose among all Fraunhofer lines those that are suitable for investigation of a specific phenomenon and to get the proper information about its depth-dependence, it is necessary to know the average optical depth of formation in the solar atmosphere of various Fraunhofer lines.

In this paper we present the calculated average optical depths of formation for eighteen Fraunhofer lines that are listed in THEMIS (Télescope Héliographique pour l'Etude du Magnétisme et des Instabilités Solaires) data bases.

2. ON THE METHOD OF CALCULATIONS

As Gurtovenko and other authors pointed out several times (Gurtovenko *et al.*, 1974, 1991; Gurtovenko and Sheminova, 1983), it is important to make clear distinction between the photospheric region of origin of the emergent line radiation and the region where the line depression is mainly formed. These two regions are not identical.

The expression for the emergent line intensity I_l at the heliocentric angle θ can be written as

$$I_l(\theta) = \int_0^\infty F_e d\tau_\lambda, \tag{1}$$

where τ_λ is the continuum optical depth and F_e is the emission contribution function. Eq.(1) reflects the usual point of view in which the radiation emerging in the line is a sum of the radiation emerging from elementary layers at different atmospheric depths τ_λ. The average optical depth at which the emergent intensity is formed is given as

$$\bar{\tau}_{\lambda e} = \frac{\int_0^\infty \tau_\lambda F_e d\tau_\lambda}{\int_0^\infty F_e d\tau_\lambda} \tag{2}$$

The contribution function F_e determines the weight of the relevant layers in contributing to the whole emerging intensity.

Fraunhofer line arises on the background of the continuum radiation as a result of an additional source of selective absorption forming a depression on the background. By analogy to Eqs.(1) and (2) we can write the expression for the line depression (D_l) and the average optical depth at which the line depression is formed $\bar{\tau}_{\lambda d}$ as

$$D_l(\theta) = \int_0^{\infty} F_d d\tau_\lambda \quad , \quad \bar{\tau}_{\lambda d} = \frac{\int_0^{\infty} \tau_\lambda F_d d\tau_\lambda}{\int_0^{\infty} F_d d\tau_\lambda} , \quad (3)$$

where F_d is the depression contribution function.

These two approaches do not reflect just two mathematical ways to get the observed value of the line radiation. There is a clear physical meaning of the second approach concerning F_d and $\bar{\tau}_{\lambda d}$. The additional source of selective absorption has its own depth distribution. Its maximum influence on the background continuum radiation is not necessarily located at depths where main part of the observed radiation originated, i.e., $\bar{\tau}_{\lambda e} \neq \bar{\tau}_{\lambda d}$.

Moreover, different sources of selective absorption resulting in the appearance of various Fraunhofer lines, have different depth distributions and differently influence the emerging radiation. This is important when we are dealing with weak lines (Gurtovenko and Ratnikova, 1974). For them $\bar{\tau}_{\lambda e}$ is very similar for all lines, practically equal to average optical depth of the continuum that is not true.

When the depth dependence and the depth range of a specific solar phenomenon are investigated, we have to look at the depth range of F_d. If those two regions are incompatible, the phenomenon under investigation could leave the line completely insensitive to it (Gurtovenko *et al.*, 1991).

Under LTE conditions the general expression for the depression contribution function (Gurtovenko *et al.*, 1991, Eq.(3)) becomes the Unsöld-Pecker contribution function:

$$F_d = g'(\tau_\lambda, \theta)\, \eta(\tau_\lambda)\, e^{-\tau_l}, g'(\tau_\lambda, \theta) = \int_{B(\tau_\lambda)}^{B(\infty)} e^{-\tau_\lambda} dB \quad (4)$$

where $\eta = k_l/k_c$ is the ratio between line and continuum absorption coefficients, τ_l is the line optical depth, B is the Planck function (source function $S = B$ under LTE). F_d has clear physical meaning: it is the energy contributed by elementary layers at different depths in the atmosphere to the observed line depression.

3. RESULTS AND DISCUSSION

Under LTE conditions we calculated the synthetic line profiles for eighteen Fraunhofer lines listed in Table 1. The calculations refer to the line intensity at the solar disk center. In our calculations we used the classical expression for natural broadening (see e.g., Gray, 1976), the Van der Waals interaction potential for the collisional broadening caused by interactions with neutral perturbers (hydrogen atoms only) within the theory of Lindholme (1945) and Foley (1946) and simple theory of collisional broadening caused by interactions with charged perturbers (electrons only) for neutral atoms (Dimitrijević and Konjević, 1986). Doppler broadening is taken into account both thermal and microturbulence motions simultaneously. The microturbulence depth distribution is given in the atmosphere model and it is the same in all used models. We did not assume any macroturbulence broadening.

For the solar atmosphere we used the six models, A through F, given by Vernazza *et al.* (1981). The set of these six models for the quiet Sun is based on various observed brightness components of the EUV continuum ranging from a dark cell center (model A) to a very bright network element (model F). The model C represents the average quiet Sun.

For all lines listed in Table 1 we calculated the average optical depth of formation of the line profile center using both emission and depression contribution function ($\bar{\tau}_{500e}$ and $\bar{\tau}_{500d}$) and the average optical depth of formation of the continuum radiation $\bar{\tau}_{500c}$. It is convinient to relate the average optical depth to the wavelength $\lambda = 500nm$.

The atomic parameters for the lines and the calculation results are given in Table 1., where columns contain respectively: the line identification with its wavelength (λ) and multiplet number (Mt), the excitation potential of the lower level in the transition (E_l), the oscillator strength (f_{lu}), Landé $\bar{g}$-factor and logarithm of the average optical depth of formation of the line depression ($\log \bar{\tau}_{500d}$) for models A through F. E_l values for calcium, chromium and iron lines were taken from Bashkin and Stoner (1975), Sugar and Corliss (1977), Corliss and Sugar (1982), respectively. f_{lu} values were taken from Wiese *et al.*, (1969), Younger *et al.*, (1981), Fuhr *et al.*, (1981) and Boyarchuk and Savanov (1985), respectively.

Selected lines are to be used in the investigation of solar magnetic field, motions and different instabilities in the atmosphere. The range of lower level excitation potential should provide a good coverage of the whole photosphere and lower chromosphere. Various values of Landé $\bar{g}$-factors that we calculated assuming the L-S coupling in the atoms, should provide different responses of lines to the magnetic field.

For all investigated Fraunhofer lines we have $\bar{\tau}_{500e} > \bar{\tau}_{500d}$ and $\bar{\tau}_{500d}$ considerably less than $\bar{\tau}_{500c}$. This is true for all models, A through F. For the most of the lines and for all models $\bar{\tau}_{500d} > \tau_{500}(T_{min})$, where $\tau_{500}(T_{min})$ designates the location of the temperature minimum in the model. This implies that the sources of the selective absorption are located in the photosphere if the last one is defined as the region below temperature minimum.

Table 1. The average optical depth of formation of the line profile center in the solar atmosphere models of Vernazza *et al.* (1981)

					$\log \bar{\tau}_{500d}$					
λ (nm)	Mt.	E_l (eV)	f_{lu}	$\bar{g}$	A	B	C	D	E	F
CaI 610.27	3	1.88	0.129	2.000	-3.22	-3.11	-2.95	-2.87	-2.80	-2.72
CaI 612.22	3	1.89	0.121	1.750	-3.72	-3.53	-3.34	-3.26	-3.19	-3.10
CaI 616.22	3	1.90	0.121	1.250	-3.87	-3.72	-3.52	-3.40	-3.30	-3.23
CrI 524.76	18	0.96	0.033	2.500	-3.41	-3.22	-3.00	-2.88	-2.77	-2.67
FeI 522.55	1	0.11	5.42(-6)	2.250	-3.52	-3.36	-3.15	-3.02	-2.88	-2.75
FeI 525.02	1	0.12	1.15(-5)	3.000	-3.33	-3.18	-2.93	-3.78	-2.61	-2.50
FeI 617.33	62	2.22	3.400(-4)	2.500	-2.38	-2.32	-2.20	-2.13	-2.00	-2.02
FeI 621.34	62	2.22	6.964(-4)	2.000	-2.91	-2.85	-2.74	-2.86	-2.54	-2.50
FeI 621.93	62	2.20	7.431(-4)	2.000	-3.24	-3.19	-3.09	-3.02	-2.95	-2.86
FeI 633.53	62	2.20	8.337(-4)	1.167	-3.29	-3.24	-3.15	-3.08	-3.02	-2.92
FeI 630.15	816	3.65	2.000(-2)	1.667	-2.80	-2.79	-2.76	-2.72	-2.64	-2.62
FeI 630.25	816	3.69	1.671(-2)	2.500	-2.32	-2.30	-2.26	-2.20	-2.12	-2.14
FeI 633.68	816	3.69	3.200(-2)	2.000	-2.73	-2.72	-2.69	-2.65	-2.55	-2.56
FeI 741.12	1077	4.28	5.141(-2)	1.000	-2.43	-2.43	-2.41	-2.38	-2.27	-2.31
FeI 744.57	1077	4.26	7.497(-2)	1.250	-2.41	-2.87	-2.86	-2.83	-2.80	-2.75
FeI 749.17	1077	4.30	2.360(-2)	1.500	-1.68	-1.67	-1.65	-1.64	-1.52	-1.61
FeI 749.51	1077	4.22	7.011(-2)	1.350	-3.00	-3.01	-3.00	-2.97	-2.95	-2.89
FeI 751.10	1077	4.18	9.091(-2)	1.400	-3.19	-3.22	-3.20	-3.19	-3.15	-3.12

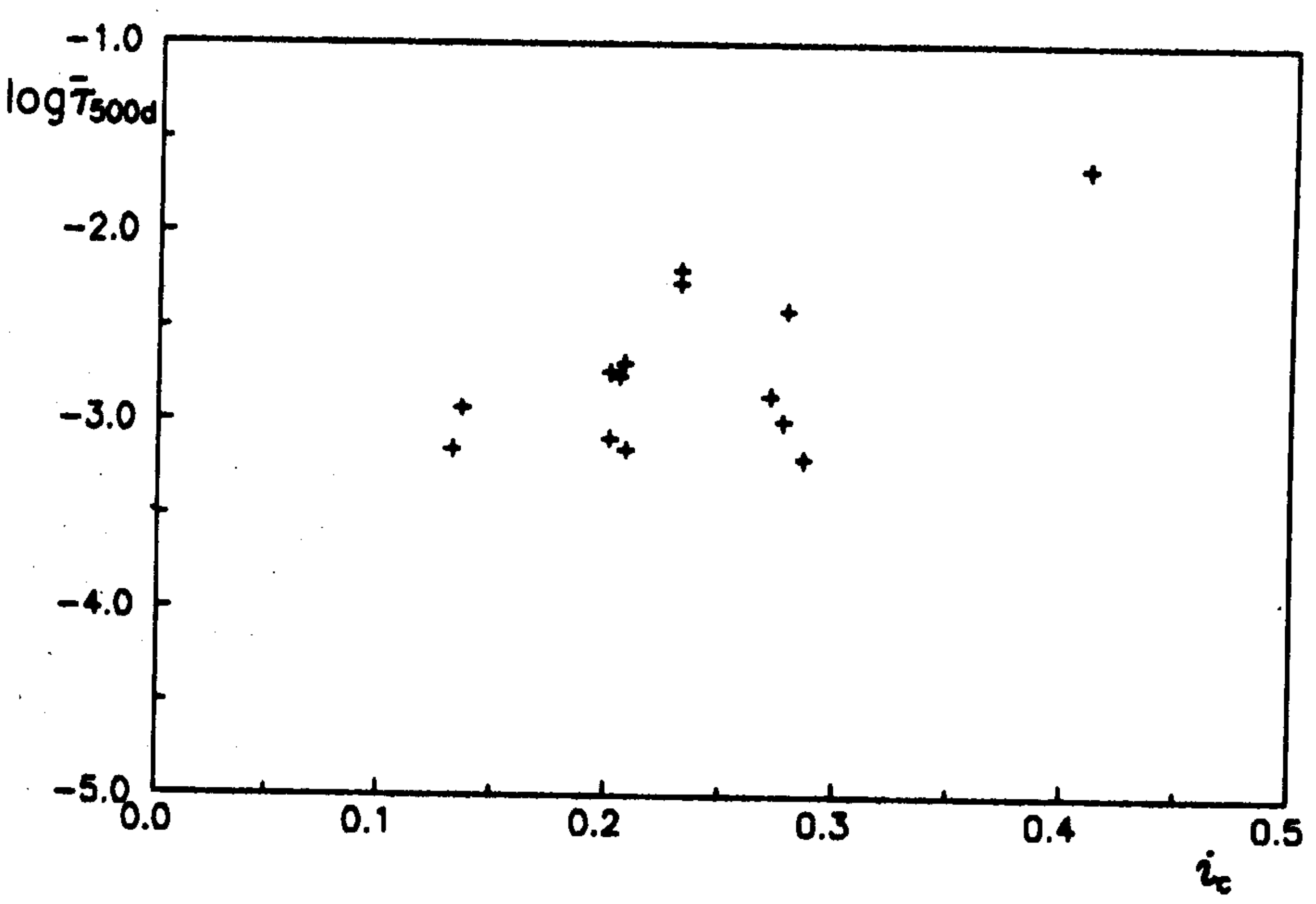

Fig. 1.a The average optical depth of line profile center formation ($\log \bar{\tau}_{500d}$) vs. central residual intensity (i_c) for iron lines for model C.

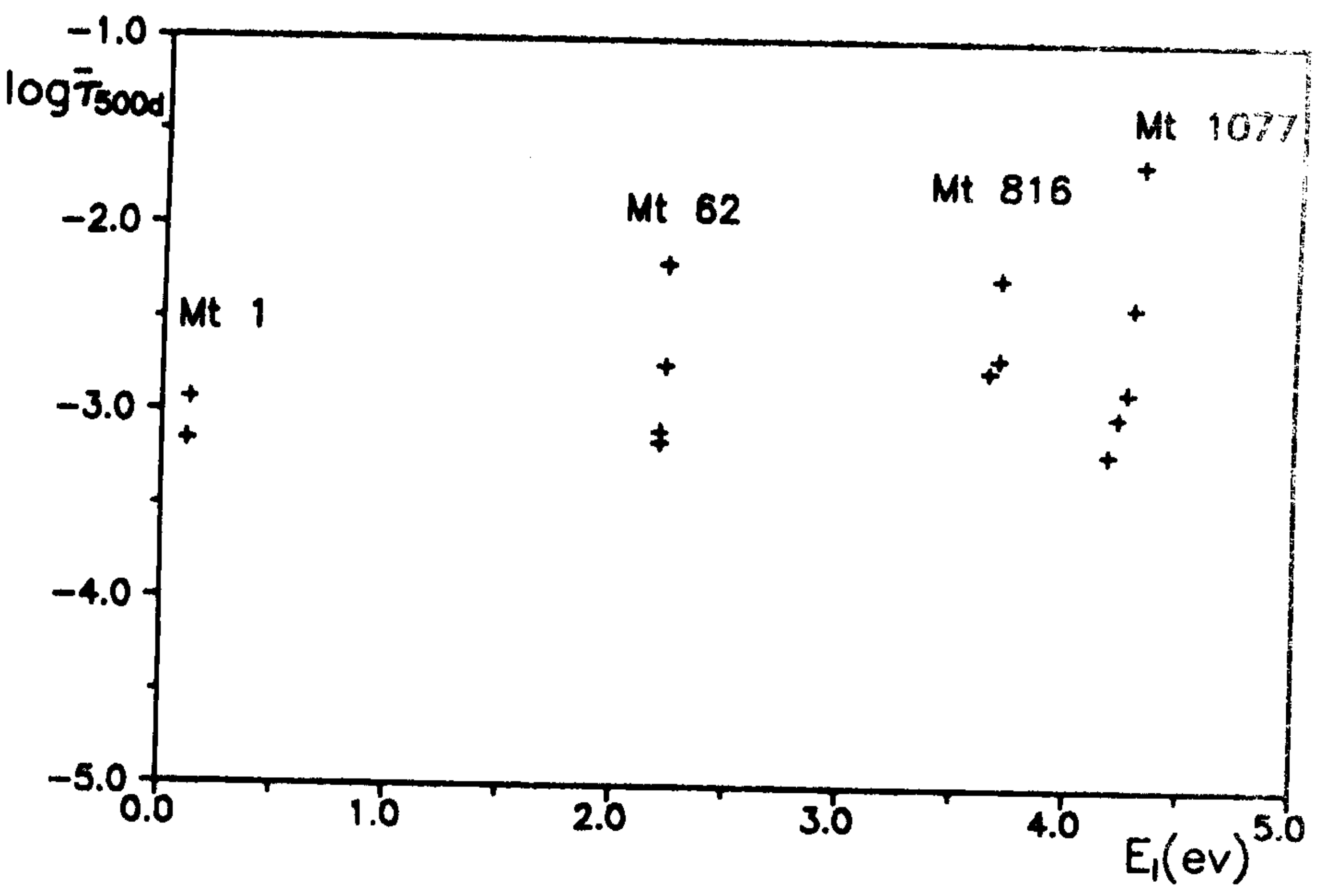

Fig. 1.b The average optical depth of line profile center formation ($\log \bar{\tau}_{500d}$) vs. excitation potential of lower level for iron lines for model C (Mt 1077, 816, 62, 1 are the multiplet numbers).

Table 1. shows that $\bar{\tau}_{500d}$ values depend on the line intensity as well as on the atomic parameters involved. For weak Fraunhofer lines $\bar{\tau}_{500d}$ is determined mainly by the excitation potential of the lower level. With increasing excitation potential $\bar{\tau}_{500d}$ increases (Gurtovenko and Ratnikova, 1974). Since our lines are not weak, we examined the behaviour of $\log \bar{\tau}_{500d}$ vs. central residual intensity and excitation potentials of the lower level (Figs. 1.a and 1.b respectively) for a group of fourteen Fe lines using the C model. In other models the behaviour of those lines is the same. There is no clear functional dependence on either of the parameters, although Fig. 1.a shows less data spreading then Fig. 1.b. It seems that both parameters are acting simultaneously with no sharp prevalence.

Interesting fact within each multiplet appears in Fig. 1.b. The bigger the log($g_l f_{lu}$) is, the higher in the atmosphere the line depression is formed, where g_l is the statistical weight of the lower level in the transition. The lines with higher excitation potentials and lower values of log($g_l f_{lu}$) are formed deeper in the photosphere with the prevailing influence of log($g_l f_{lu}$). $g_l f_{lu}$ is one of the factors that determine the absorber concentration. Consequently, strong lines cannot be formed in the deep photosphere and then the maximum concentration of the absorbing particles is moved to higher layers in the photosphere. The same is valid for Ca lines from the Table 1.

If we compare the values of $\log \bar{\tau}_{500d}$ for every line for all atmosphere models we can see that the line depression is formed deeper in the photosphere when we are going from model A to model F. The same is valid for $\log \bar{\tau}_{500e}$ and $\log \bar{\tau}_c$. Also, the lines become less intense, the central residual intensity is increasing from model A to model F. It appears that the lines with lower values of the excitation potential experience the greater change in $log \bar{\tau}_{500d}$.

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О СРЕДЊИМ ОПТИЧКИМ ДУБИНАМА ФОРМИРАЊА НЕКИХ ФРАУНХОФЕРОВИХ ЛИНИЈА

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Израчунате су вредности средње оптичке дубине формирања линијске депресије у центру сунчевог диска за осамнаест фраунхоферових линија за шест модела сунчеве атмосфере Vernazzae и др. (1981). Испитиване су неке правилности у понашању средњих оптичких дубина у односу на централни резидуални интензитет профила линија и ексцитациони потенцијал доњег нивоа прелаза.