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The electron-impact broadening effect in CP stars: the case of La II, La III, Eu II, and Eu III lines

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Abstract. The electron-impact widths and shifts for six Eu II lines and widths for three La II, and six La III multiplets have been calculated by using the modified semiempirical method. Estimation for Stark widths of 664.506 nm (Eu II) and 666.634 nm (Eu III) lines are given as well. The influence of the electron-impact mechanism on line shapes and equivalent widths in hot star atmospheres has been considered.

Key words: atomic data – plasmas – stars: chemically peculiar

1. Introduction

The lines of the ionized rare earth elements (REE) are present in the spectra of CP stars in a wide temperature domain (see e.g. Jaschek & Jaschek 1974, Bonsack & Wolf 1980, Magazzu & Cowley 1986, Ryabchikova & Ptitsyn 1986, Cowley & Greensberg 1988, Van't Veer et al. 1988, Sadakane 1993, Kupka et al. 1996, Gelbmann et al. 1997, Ryabchikova et al. 1997, 1999, etc), and many review articles on abundances of the REE exist (e.g. Jaschek & Jaschek 1974, Bonsack & Wolf 1980, Cowley 1984, Sadakane 1993). Cowley (1984) discussed the observed stellar lines of the REE and gave element by element summaries. Usually, REE abundance analysis is based on the lines of the first ions, which have experimentally determined oscillator strengths, but due to low ionization potentials the second ions of the REE are dominant in stellar atmospheres. The lack of atomic data for the lines of second ions of the REE did not allow to use them for abundance determinations, although line identifications were successfull. For example, Cowley (1984) identified Dy III lines in spectra of a few magnetic stars, Cowley & Greenberg (1988) surveyed lines of doubly ionized REE in UV spectra of five magnetic stars, Mathys & Cowley (1992) presented Pr III identification in optical spectra of a number of CP stars. The first calculations of the oscillator strengths for Ce III lines by Bord et al. (1997) made it possible to use the lines of the second ions of the REE for abundance determinations. Bord et al. (1997) analyzed Ce III lines in spectra of CP stars HD 200311, HD 192913, and HR 465, Cowley & Bord (1998) analyzed Nd III lines in CP stars γ Equ, and HD 168733, Ryabchikova et al. (1999) provided an identification and quantitative analysis of Eu III lines in the optical spectra of 10 CP stars.

The spectral lines of singly ionized lanthanum and europium are present in solar as well as in stellar spectra (see e.g. Grevesse & Blanquet 1969, Molnar 1972, Adelman 1987, Sadakane 1993, etc.). For example, Sadakane (1993) suggested overabundance of La in α CMa and o Peg, two hot Am-type stars, and Ryabchikova et al. (1999) revised abundance of Eu in 10 magnetic stars taking into account hyperfine structure and magnetic effects. The lines of Eu II in the optical spectra of CP stars are usually very strong and lie in the damping part of the curve-of-growth. Since in A-type stars mentioned here Stark broadening is the main pressure broadening mechanism (see e.g. Dimitrijević 1989) the corresponding data on Stark broadening of stellar spectral lines are needed for a number of astrophysical problems including the line formation and the abundance determinations.

Due to the poor knowledge on the energy levels as well as on the realiable transition probabilities for the rare earth emitters, the approximate methods are suitable for Stark broadening calculations. Here we have applied the modified semiempirical approach – MSE (Dimitrijević & Konjević 1980, Dimitrijević & Kršljanin 1986, Popović & Dimitrijević 1996a, 1997) whose applicability for complex spectra has been tested several times (see e.g. Popović & Dimitrijević 1996ab, 1997). This method is applicable only for the Stark broadening of ion lines while for neutral atom lines there exists e.g. the method of Dimitrijević & Konjević (1986).

In order to provide a complete set of Stark broadening data for astrophysical purposes, we started a project to calculate such data for a number of spectral lines of the ionized REE (see Popović & Dimitrijević 1998a). Here we present the Stark widths for three La II and six La III mulitplets, and Stark widths and shifts for six Eu II lines by using the MSE. Also, for Eu II λ 664.505 nm and for Eu III λ 666.635 nm lines estimates of the electron impact widths have been performed. Our data are the first Stark broadening calculations for spectral lines of ionized lanthanum and europium. For resonance lines of La II and Eu II

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Table 1. Stark full widths (FWHM) and shifts for Eu II lines, calculated within the modified semiempirical approach, as a function of temperature. The electron density is $10^{23}\mathrm{m}^{-3}$

Transition	T (K)	W (nm)	d (nm)
	5000.	0.293E-01	-0.432E-02
$6s\,^7S^0_3 - 6p\,^7P_2$	10000.	0.203E-01	-0.307E-02
	20000.	0.141E-01	-0.218E-02
$\lambda = 390.710$ nm	30000.	0.115E-01	-0.177E-02
	40000.	0.102E-01	-0.153E-02
	50000.	0.951E-02	-0.140E-02
	5000.	0.295E-01	-0.436E-02
$6s\,^7S^0_3 - 6p\,^7P_3$	10000.	0.205E-01	-0.309E-02
	20000.	0.142E-01	-0.220E-02
$\lambda = 393.048$ nm	30000.	0.116E-01	-0.179E-02
	40000.	0.103E-01	-0.155E-02
	50000.	0.959E-02	-0.142E-02
	5000.	0.300E-01	-0.436E-02
$6s\,^7S^0_3 - 6p\,^7P_4$	10000.	0.208E-01	-0.309E-02
	20000.	0.144E-01	-0.220E-02
$\lambda = 397.196$ nm	30000.	0.118E-01	-0.179E-02
	40000.	0.105E-01	-0.155E-02
	50000.	0.974E-02	-0.142E-02
	5000.	0.570E-01	-0.173E-01
$6s\,^9S^0_4 - 6p\,^9P_3$	10000.	0.397E-01	-0.125E-01
	20000.	0.276E-01	-0.916E-02
$\lambda = 420.505$ nm	30000.	0.226E-01	-0.776E-02
	40000.	0.200E-01	-0.705E-02
	50000.	0.185E-01	-0.671E-02
	5000.	0.557E-01	-0.169E-01
$6s\,^9S^0_4 - 6p\,^9P_4$	10000.	0.388E-01	-0.122E-01
	20000.	0.270E-01	-0.897E-02
$\lambda = 412.970$ nm	30000.	0.221E-01	-0.759E-02
	40000.	0.195E-01	-0.688E-02
	50000.	0.181E-01	-0.654E-02
	5000.	0.451E-01	-0.391E-02
$6s\,^9S^0_4 - 6p\,^9P_5$	10000.	0.314E-01	-0.278E-02
	20000.	0.219E-01	-0.198E-02
$\lambda = 381.967$ nm	30000.	0.179E-01	-0.161E-02
	40000.	0.158E-01	-0.142E-02
	50000.	0.146E-01	-0.132E-02

however, simple estimates of Stark widths and shifts, based on the regularities and systematic trends, exist (Lakićević 1983).

2. Method of calculations

In the case of three La II and six La III transitions, it was possible to use the MSE approach (Dimitrijević & Konjević 1980, Dimitrijević & Kršljanin 1986) in adequate way and calculate Stark widths (W - full width at half maximum) for the multiplet as a whole. For the simple spectrum Stark broadening parameters of different lines are nearly the same within a multiplet (Wiese & Konjević 1982, 1992). Consequently, one may take the averaged atomic data for a multiplet as a whole and calculate the corresponding Stark widths and shifts. If the wavelength of a particular line within the multiplet differs significantly from

Table 2. Stark full widths (FWHM) for La II and La III lines calculated within the modified semiempirical approach. The electron density is $10^{23}\mathrm{m}^{-3}$. The averaged wavelength of the multiplet is denoted as $\langle\lambda\rangle$.

Transition	T (K)	W (nm)
	5000.	0.336E-01
La II	10000.	0.232E-01
$a\,^3P - y\,^3D^0$	20000.	0.160E-01
	30000.	0.131E-01
$\langle\lambda\rangle = 463.20$ nm	40000.	0.116E-01
	50000.	0.109E-01
	5000.	0.493E-01
La II	10000.	0.348E-01
$a\,^3D - y\,^3D^0$	20000.	0.246E-01
	30000.	0.201E-01
$\langle\lambda\rangle = 403.58$ nm	40000.	0.174E-01
	50000.	0.148E-01
	5000.	0.219E-01
La II	10000.	0.152E-01
$a\,^3F - y\,^3D^0$	20000.	0.104E-01
	30000.	0.853E-02
$\langle\lambda\rangle = 379.44$ nm	40000.	0.756E-02
	50000.	0.707E-02
	5000.	0.260E-01
La III	10000.	0.182E-01
$6s\,^2S - 6p\,^2P^0$	20000.	0.126E-01
	30000.	0.103E-01
$\langle\lambda\rangle = 328.01$ nm	40000.	0.892E-02
	50000.	0.807E-02
	5000.	0.105E-01
La III	10000.	0.734E-02
$6s\,^2S - 7p\,^2P^0$	20000.	0.522E-02
	30000.	0.440E-02
$\langle\lambda\rangle = 124.28$ nm	40000.	0.400E-02
	50000.	0.376E-02
	5000.	0.747
La III	10000.	0.522
$7s\,^2S - 7p\,^2P^0$	20000.	0.374
	30000.	0.320
$\langle\lambda\rangle = 854.39$ nm	40000.	0.295
	50000.	0.281
	5000.	0.453E-01
La III	10000.	0.317E-01
$6p\,^2P^0 - 7s\,^2S$	20000.	0.226E-01
	30000.	0.191E-01
$\langle\lambda\rangle = 261.31$ nm	40000.	0.173E-01
	50000.	0.162E-01
	5000.	0.231E-01
La III	10000.	0.161E-01
$6p\,^2P^0 - 6d\,^2D$	20000.	0.115E-01
	30000.	0.978E-02
$\langle\lambda\rangle = 259.32$ nm	40000.	0.889E-02
	50000.	0.839E-02
	5000.	0.556
La III	10000.	0.388
$6d\,^2D - 7p\,^2P^0$	20000.	0.278
	30000.	0.238
$\langle\lambda\rangle = 876.37$ nm	40000.	0.220
	50000.	0.210

the averaged wavelength $\langle\lambda\rangle$ of the multiplet one may obtain more accurate values for each line by scaling multiplet values for widths and shifts:

$$W_{\rm line} = (\frac{\langle\lambda\rangle}{\lambda})^2 \cdot W, \quad (1)$$

In the above expression W and $\langle\lambda\rangle$ are values for the multiplet, and $W_{\rm line}$ and λ refer to a particular line of the multiplet.

It is not always possible to apply this approximation for complex spectra. If irregularities of atomic energy level structure, forbidden and intercombination transitions influence different lines of the multiplet in a different way, we have to calculate Stark broadening data for each line separately (Dimitrijević 1982, Popović & Dimitrijević 1997, Dimitrijević & Tankosić 1999). Such case is realized for Eu II and Eu III lines considered in our paper.

In the case of Eu II, taking into account very complex spectrum of this emitter and the absence of designation for higher levels, we were able to calculate the electron-impact broadening parameters only for six 6s-6p transitions using the MSE approach. Due to the complex spectrum we have applied here this method as it was described in Popović & Dimitrijević (1996a, 1997). We have estimated also the electron-impact width for Eu II ($5d\,^9D^0_6 - 6p\,^9P_5$) λ 664.506 nm line using the MSE approach with the estimate of the perturbation of the $5f$ levels (in accordance with Popović & Dimitrijević 1998b). We have also estimated Stark width for Eu III λ 666.635 nm line using the simplified MSE method (Dimitrijević & Konjević 1987) in LS coupling approximation.

Atomic energy levels needed for calculations have been taken from Sugar & Spector (1974) and from Martin et al. (1978). Matrix elements were calculated by the method of Bates & Damgaard (1949). The multiplet factors for calculations of La II and La III Stark broadening parameters were taken from Shore & Menzel (1968). Since for nonet terms the line factors are absent in the tables of Shore & Menzel (1968), the corresponding factors for Eu II lines were calculated according to formula:

$$\Re_{\rm line} = \sqrt{2J+1}\sqrt{2J'+1}\begin{Bmatrix} S & J & L \\ 1 & L' & J' \end{Bmatrix} \quad (2)$$

where S is the total spin; J and J' are total angular momentum quantum numbers; while L and L' are total azimuthal quantum numbers. The quantum numbers of the perturbing level are denoted with the primes.

The details of the MSE and simplified MSE method have been given several times (Dimitrijević & Konjević 1980, Dimitrijević & Kršljanin 1986, Dimitrijević & Konjević 1987, Popović & Dimitrijević 1996a, 1997) and will not be repeated here again.

3. Results and discussion

Stark widths and shifts for six Eu II lines, and Stark widths for three La II and six La III multiplets are presented in Tables 1 and 2 for different temperatures, and for electron density of $10^{23}\rm m^{-3}$.

Table 3. Estimated Stark full widths (W) for Eu II 664.505 nm and Eu III 666.63 nm lines. The Eu II 664.505 nm line has been calculated within the modified semiempirical approach (MSE) with estimated perturbation of $5f$ levels. The Eu III 666.65 nm line has been calculated within the simplified MSE. The results are given for an electron density of $10^{23}\rm m^{-3}$ as a function of temperature.

Transition	T (K)	W (nm)
	5000.	0.930E-01
Eu II	10000.	0.644E-01
$5d\,^9D^0_6 - 6p\,^9P_5$	20000.	0.447E-01
	30000.	0.367E-01
$\lambda = 664.505$ nm	40000.	0.327E-01
	50000.	0.306E-01
	5000.	0.354E-01
Eu III	10000.	0.247E-01
$4f^7\,^6I^0_{17/2} - 4f^65d\,^6H_{15/2}$	20000.	0.171E-01
	30000.	0.137E-01
$\lambda = 666.63$ nm	40000.	0.117E-01
	50000.	0.104E-01

Stark widths for Eu II λ 664.505 nm line calculated by the MSE method with the estimated perturbation of unknown $5f$ levels, and Stark width for Eu III λ 666.63 nm line estimated with the simplified MSE method (Dimitrijević & Konjević 1987) are given in Table 3. In order to present our results in a more convenient form for synthetic spectrum calculations, all data from Tables 1–3 were fitted with the following expression:

$$W(\,{\rm rad\,s^{-1}}) = A_0 \cdot T^{A_1}. \quad (3)$$

Here W is a full width at half maximum (FWHM) expressed in rad $\rm s^{-1}$ per electron, and constants A_0 and A_1 are determined numerically to obtain the best fit. The corresponding values of $\log A_0$ and A_1 are given in Table 4 together with the widths and shifts (in logarithmic form) per electron for T=10000 K. This temperature was chosen as the most representative for A-type stars where the Stark broadening becomes the dominant pressure broadening mechanism due to hydrogen ionization. This kind of presentation is similar to that used in the most complete set of atomic line parameters calculations by Kurucz (1993a) for Fe-peak elements.

There is no experimental data for the electron broadening parameters for La and Eu lines considered in the paper. The only estimates for the $5d^2\ ^3F - 4f5d\ ^3F^0$ (λ =580.82 nm) La II transition and the resonance Eu II line were made by Lakićević (1983) on the basis of regularities and systematic trends for the electron temperature of 20000 K and the electron density of $10^{23}\rm m^{-3}$. These estimates resulted in W=0.0338 nm; $|d|$=0.0149 nm for La II λ =580.82 nm, and in W=0.032 nm; $|d|$=0.014 nm for the resonance transition of Eu II. The energy level $4f\ ^3F^0$ in Lakićević (1983) paper is obviously erroneous. We suppose that this is $5d\,^3F^0$ level in fact, but since we have not found the corresponding $5f$ levels in the literature the adequate MSE calculations cannot be performed. Concerning the results for Eu II, neither the transition nor the wavelength are specified in Lakićević (1983), making the comparison impossible.

Table 4. The Stark widths and shifts W (rad s^{-1}) and d (rad s^{-1}) per electron for T=10000 K, and constants $A_{0,1}$ as described in the text.

Ion λ (nm)	log[W(rad s^{-1})]	log A_0	A_1	log[d(rad s^{-1})]
Eu II 397.196	-5.6052	-0.36188E+01	-0.49620	-6.4333
Eu II 393.048	-5.6024	-0.36144E+01	-0.49674	-6.4242
Eu II 390.710	-5.6014	-0.36104E+01	-0.49733	-6.4218
Eu II 420.505	-5.3740	-0.33899E+01	-0.49574	-5.8759
Eu II 381.967	-5.3900	-0.34446E+01	-0.48596	-6.4458
Eu II 412.970	-5.3682	-0.33839E+01	-0.49580	-5.8707
Eu II 664.505	-5.5613	-0.35927E+01	-0.49160	
Eu III 666.635	-5.9803	-0.38493E+01	-0.53323	
La II $\langle 379.440 \rangle$	-5.7017	-0.36967E+01	-0.50131	
La II $\langle 403.580 \rangle$	-5.3955	-0.33450E+01	-0.51257	
La II $\langle 463.200 \rangle$	-5.6913	-0.36932E+01	-0.49910	
La III $\langle 328.010 \rangle$	-5.4969	-0.34520E+01	-0.51145	
La III $\langle 124.280 \rangle$	-5.0483	-0.32345E+01	-0.45202	
La III $\langle 259.320 \rangle$	-5.3461	-0.35580E+01	-0.44516	
La III $\langle 261.310 \rangle$	-5.0585	-0.32468E+01	-0.45141	
La III $\langle 854.390 \rangle$	-4.8709	-0.31376E+01	-0.43130	
La III $\langle 876.370 \rangle$	-5.0218	-0.32939E+01	-0.42986	

In order to test the importance of the electron-impact broadening effect in stellar atmospheres, we have synthesized the line profiles of Eu II λ=420.505 nm and Eu III λ=666.63 nm lines using SYNTH code (Piskunov 1992) and the Kurucz's ATLAS9 code for stellar atmosphere models (Kurucz 1993b) in the temperature range of 6000 $\leq T_{\rm eff} \leq$ 16000 K, and 3.0$\leq \log g \leq$5.0. We have modified the SYNTH code, which uses $\log W$(rad s^{-1}) per electron for T=10000 K as an imput parameter replacing them by three imput parameters: A_0 and A_1 from Eq. 3 and Stark line shift (d).

For the spectrum synthezis it is more convenient to use the parameters A_0 and A_1 (from Table 4) than to take more accurate data from Tables 1–3. In Fig. 1 the comparison between calculated data (filled circles) and the fit with Eq. 3 (full line) for La III $\langle 876.37 \rangle$ is shown. We present also the result of an approximate temperature scaling (dashed line) performed as

$$W_T = W_{T_m} \cdot (\frac{T}{T_m})^{-1/2}, \quad (4)$$

(T_m=10000 K) that may be used in astrophysics for ion lines.

As we can see from Fig. 1, if a particular accuracy is not necessary, Eqs. (3) and (4) provide a good approximation, especially for large scale calculations.

The synthesized line profiles for Eu II 420.505 nm line calculated for the model with $T_{\rm eff}$=9500 K, $\log g$=4.5 and the europium abundances A=log(Eu/H)=-5.9 and -7.5 are shown in Fig. 2. One can see that Stark effect leads to the growth of the line wings and hence to the increase of the line equivalent width (EW). In our cases enhancement factors are more than 2 for A=-5.9 and 1.6 for A=-7.5.

In Fig. 3(a,b) we show the ratio of the equivalent widths – $EW_{\rm St}/EW_0$ – as a function of the effective temperature. Here $EW_{\rm St}$ and EW_0 are the equivalent widths of the line calculated with and without Stark broadening effect. The calculations were performed for Eu II 420.505 nm (Fig. 3a) and for Eu III 666.63 nm (Fig. 3b) lines with the europium abundance log(Eu/H)= -6.9.

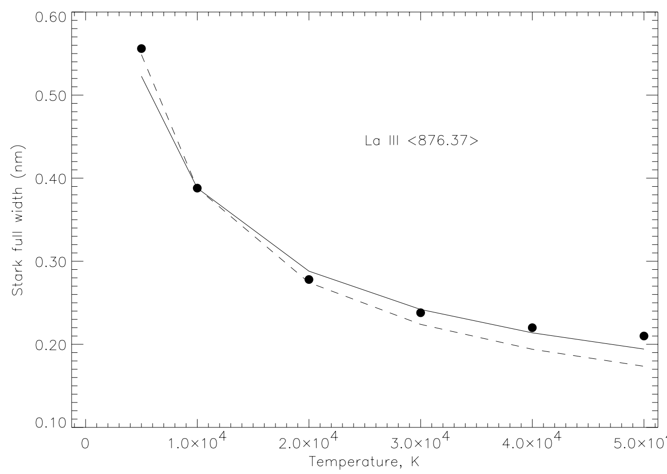

Fig. 1. Stark widths for La III $6d\,^2D - 7p\,^2P^0$ ($\langle\lambda\rangle$ =876.37 nm) line as a function of the electron temperature. Data from Table 2 are shown by filled circles, data obtained with the different approximations are shown by full line (Eq. 3) and by dashed line (Eq. 4), respectively

As one can see from Fig. 3(a,b) for Eu II 420.505 nm line the electron impact broadening has its maximum effect at $T_{\rm eff} \approx$ 8000–9000 K, while for Eu III 666.63 nm line this effect is important for $T_{\rm eff} >$ 8000 K and maximum is not present. Different trends in the dependence of the electron broadening effect on effective temperature for two lines may be explained by difference in the ionization potentials of Eu II and Eu III. The ionization potential of Eu II is 11.241 eV, and for higher effective temperatures this ion is practically absent in the layers where the electron impact broadening is important and where Eu III becomes to be a dominant ion. The small minimum around $T_{\rm eff}$=12000 K in Fig. 3b may be connected with the specific depth formation of the Eu III line. A decrease of the Stark broadening effect for Eu II

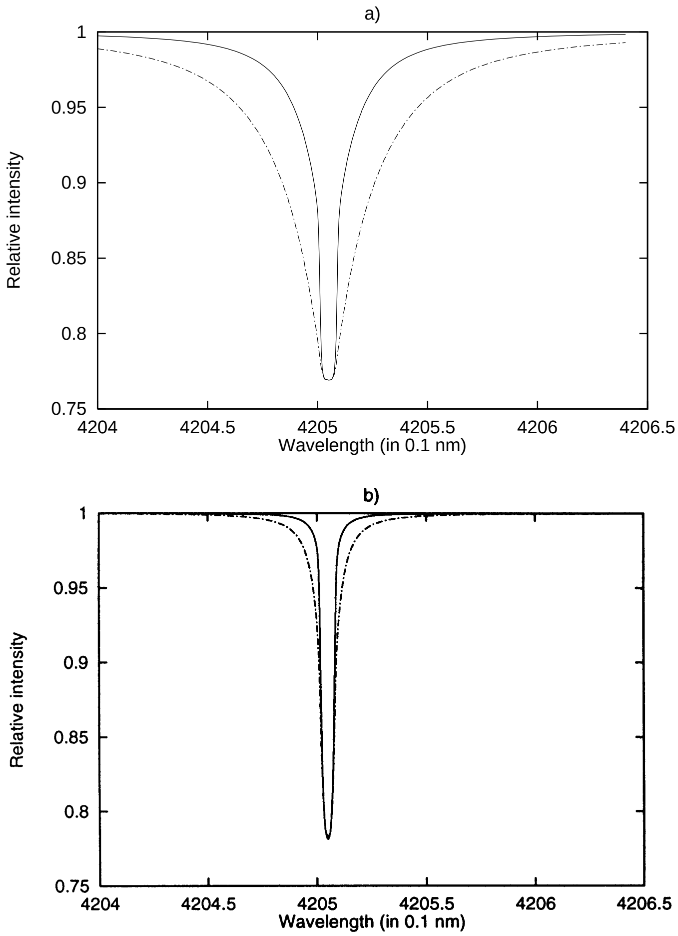

Fig. 2. The line profile of Eu II 420.505 nm line synthesized with Stark broadening mechanism taken into account (dashed line) and without it (full line). The calculations have been performed for the atmosphere model with $T_{\rm eff}$=9500 K and $\log g$=4.5. The abundances of europium are a) log(Eu/H)=-5.9 and b) log(Eu/H)=-7.5

line towards the lower temperatures when this ion becomes to be dominant occures due to rapid decrease of the electron density.

In Fig. 4 the influence of Stark broadening effect for different $\log g$ in the case of Eu III 666.63 nm line is shown. As one can see the importance of Stark broadening increases with $\log g$. This trend is expected, because the electron density, and hence the frequency of the electron-emitter collisions increases with $\log g$.

The influence of Stark broadening for Eu III 666.63 nm line as a function of europium abundance is shown in Fig. 5 for an A0 type star ($T_{\rm eff}$=10000 K, $\log$ g=4.0).

It is interesting that the influence for the considered line has maximum about A=-5.

The Stark broadening influence as well as the equivalent width increase with abundance. For higher abundances of europium the contribution of the Van der Waals broadening effect starts to be more important too. Consequently, as one can see in Fig. 5. the ratio of the equivalent widths $EW_{\rm St}/EW_0$ decreases with abundance for A$>$-5.

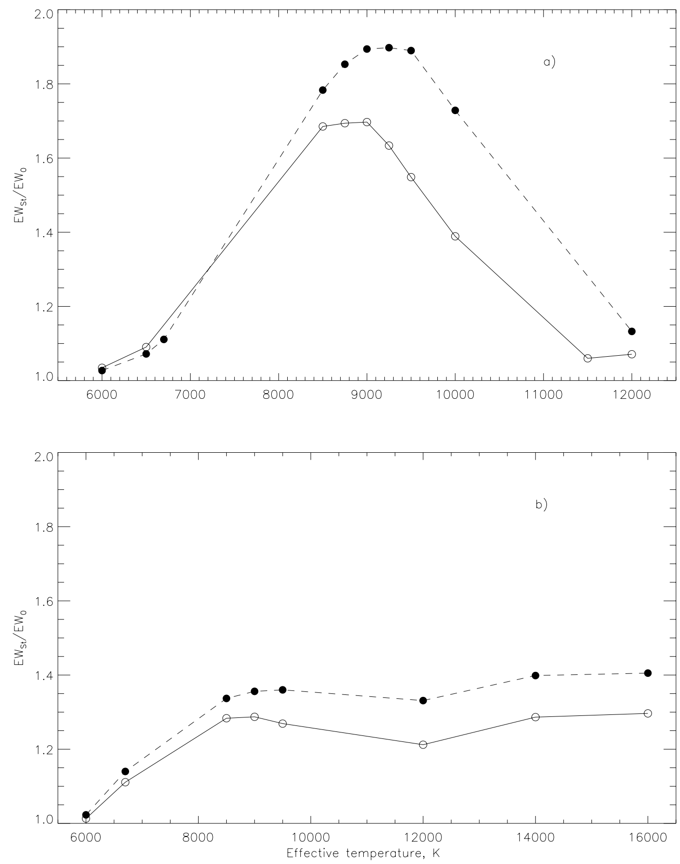

Fig. 3a and b. The ratio of equivalent widths for Eu II 420.505 nm line **a** and for Eu III 666.63 nm line **b** calculated with Stark broadening effect ($EW_{\rm St}$) and without it (EW_0) as a function of effective temperature. Results for $\log g$=4.0 and for $\log g$=4.5 are shown by the open circles and full circles respectively

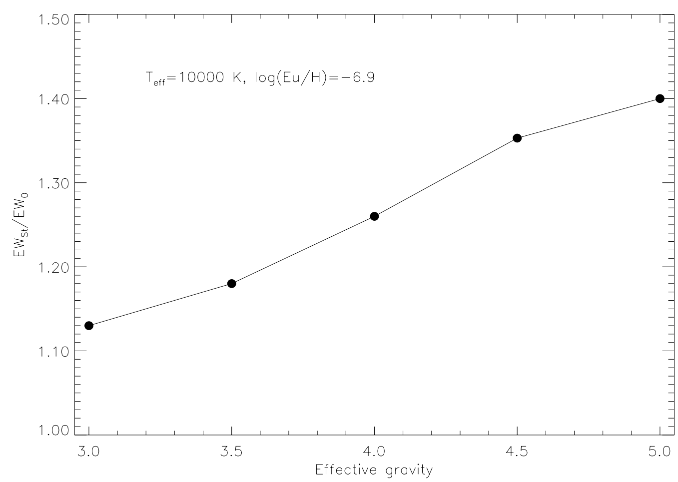

Fig. 4. The ratio of the equivalent widths $EW_{\rm St}/EW_0$ as a function of $\log g$ for Eu III 666.63 nm line

4. Conclusions

The Stark broadening widths and shifts for Eu II, Eu III, La II and La III lines calculated within the modified semiemprical approach are presented as the first reliable data on the Stark

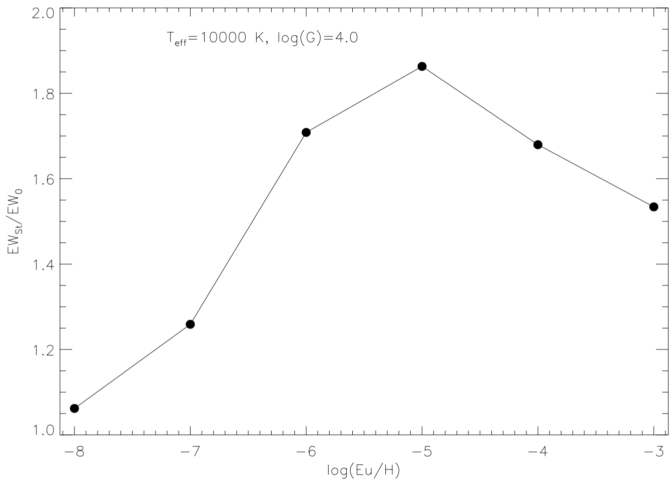

Fig. 5. The ratio of $EW_{\rm St}/EW_0$ for Eu III 666.63 nm line as a function of Eu abundance

broadening of the rare-earth elements, which is important in particular for the abundance analysis of CP stars.

The importance of the Stark broadening effect in stellar atmospheres under different conditions has been considered. Stark broadening becomes to be significant in hot stars, and it should be taken into account in the analysis of stellar spectral lines for the $T_{\rm eff}>$7000 K in particular if europium is overabundant.

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