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Stark broadening of Ga I spectral lines*

M. S. Dimitrijević[1,2], M. Dačić[1,2], Z. Cvetković[1,2], and Z. Simić[1,2]

[1] Astronomical Observatory, Volgina 7, 11160 Belgrade, Serbia and Montenegro
e-mail: `mdimitrijevic@aob.bg.ac.yu`
[2] Institute Isaac Newton of Chile, Yugoslavia Branch

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Abstract. Stark broadening of the 18 Ga I transitions has been analyzed within the framework of the semiclassical perturbation method. Results obtained have been compared with available experimental and theoretical data and used for the consideration of the influence of the Stark broadening effect in stellar atmospheres

Key words. line: profiles – atomic data – atomic processes – line: formation – stars: atmospheres

1. Introduction

Data on the Stark broadening of neutral gallium spectral lines are of interest not only for the laboratory but also for astrophysical plasma research as e.g. for stellar spectra analysis and synthesis, for gallium abundance determination (Smith 1996) and opacity calculations (Seaton 1988). Spectral lines of this element are present in the Solar spectrum (see e.g., Moore et al. 1966; Grevesse 1984). Moreover Jaschek & Jaschek (1987) have found gallium lines not only in the spectra of HgMn, Si-4200 and He-weak chemically peculiar stars but also in the spectra of a few stars otherwise classified as normal. Dworetsky (1993) reports on neutral gallium lines in A-type star spectra, and Ryabchikova & Smirnov (1994) in the spectrum of HgMn star Kappa Cancri. Smith (1995) investigated anomalous gallium line profiles in HgMn stars and found evidence for chemical stratification in their atmospheres. The fact that this element is often overabundant in chemically peculiar stars contributes to the astrophysical importance of gallium spectral lines. The problem of gallium in HgMn chemically peculiar stars is discussed for example in Dworetsky et al. (1998).

Zverko & Zboril (1989) tried to derive the gallium abundance of 53 Tau from Ga I 4032.98 Å and 4172.06 Å spectral lines and Smith (1996) reports on elemental abundance of gallium in normal late-B and HgMn stars. Smith (1995, 1996) concluded that HgMn stars have enhanced gallium abundances, and Zboril & Berrington (1901) have published the Non-LTE gallium equivalent widths for the most prominent gallium transitions as identified in real spectra and in (hot) mercury-manganese stars.

Data on Stark broadening parameters are also significant for the calculation of opacity coefficients (Artru 1993) in stellar interiors and envelopes. For example Rogers & Iglesias (1992, see also comment in Artru 1993) developed the OPAL code for opacity calculations, where line broadening effects (including Stark broadening) are included, as well as gallium spectral lines.

Since around $T = 10\ 000$ K (a temperature of particular interest for chemically peculiar star atmospheres) hydrogen is mainly ionized, Stark broadening is the principal pressure broadening mechanism for such plasma conditions.

With the development of space-borne telescopes and instruments like the Goddard High Resolution Spectrograph on the Hubble Space Telescope and the Keck telescopes, the quality and quantity of spectroscopic data has increased so that for their interpretation data of line profiles are of increasing interest. Additionally, Stark broadening parameters of gallium lines are of interest for the consideration of regularities and systematic trends.

The first investigations of the influence of the Stark broadening mechanism on gallium lines have been performed by Kondrat'eva & Fomichenko (1970) in a spark discharge and by Venkatesan et al. (1981). Lakićević (1983) estimated, on the basis of regularities and systematic trends, Stark width and shift of the Ga I $4p^2P^0 - 5s^2S$ transition and N'Dollo & Fabry (1987) used the semiclassical method and experimentally determined Ga I Stark widths.

Here, we will use the semiclassical perturbation approach (Sahal-Bréchot 1969a,b) to determine Stark broadening parameters of 18 Ga I transitions for conditions typical of astrophysical and laboratory plasmas. The obtained results will be compared with available experimental and theoretical values, and used for the investigation of the influence of the Stark broadening mechanism on spectral line shapes in stellar atmospheres.

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* Table 1 is also available in electronic form at the CDS via anonymous ftp to `cdsarc.u-strasbg.fr` (`130.79.128.5`) or via `http://cdsweb.u-strasbg.fr/cgi-bin/qcat?J/A+A/425/1147`

2. Results and discussion

Stark broadening parameters (the full line width at half maximum – *W* and the line shift – *d*) of neutral gallium spectral lines were determined by using the semiclassical perturbation formalism. This formalism, as well as the corresponding computer code (Sahal-Bréchot 1969a,b), has been updated and optimized several times (Sahal-Bréchot 1974, 1991; Fleurier et al. 1977; Dimitrijević & Sahal-Bréchot 1984; Dimitrijević et al. 1991; Dimitrijević & Sahal-Bréchot 1996). The calculation procedure, with the discussion of updating and validity criteria, has been briefly reviewed e.g. in Dimitrijević (1996). Atomic energy levels needed for calculations have been taken from Moore (1971). The oscillator strengths have been calculated within the Coulomb approximation (Bates & Damgaard 1949) and the tables of Oertel & Shomo (1968). For higher levels, the method of van Regemorter et al. (1979) has been used.

In Table 1 (available also in electronic form at the CDS), electron-, and proton-impact broadening parameters for 18 Ga I transitions for a perturber density of 10^{14} cm^{-3}, typical of stellar atmosphere conditions and temperatures from 2500 up to 50 000 K, are shown. Moreover, we present in Table 1 a parameter *C* (Dimitrijević & Sahal-Bréchot 1984), which gives an estimate of the maximum perturber density for which the line may be treated as isolated, when it is divided by the corresponding full width at half maximum. The validity of the impact approximation has been estimated for data shown in Table 1, by checking if the collision volume (*V*) multiplied by the perturber density (*N*) is much less than one (Sahal-Bréchot 1969a,b). When the impact approximation is not valid, the ion broadening contribution may be estimated by using the quasistatic approach (Sahal-Bréchot 1991; or Griem 1974). In the region between, where neither of these two approximations is valid, a unified type theory should be used. For example in Barnard et al. (1974), a simple analytical formula for such a case is given. The accuracy of the results obtained decreases when broadening by ion interactions becomes important.

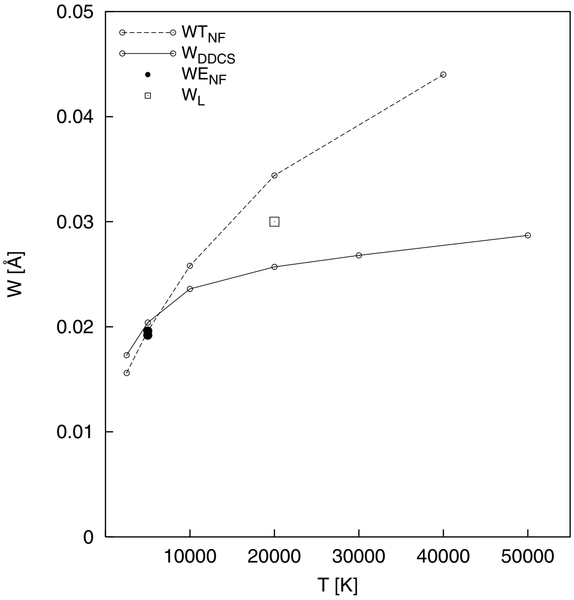

Fig. 1. Stark full widths at half maximum W[Å] for Ga I $4p^2P^0$–$5s^2S$ multiplet in function of T[K]. Theoretical calculations: W$_{DDCS}$ – present work; WT$_{NF}$ – N'Dollo & Fabry (1987); W$_{L}$ – Lakićević (1983). Experimental data: WE$_{NF}$ – N'Dollo & Fabry (1987).

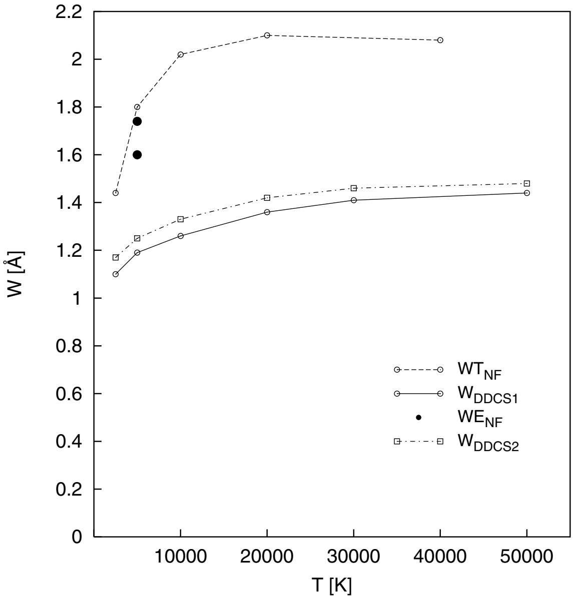

Fig. 2. Stark full widths at half maximum W[Å] for Ga I $5s^2S$–$6p^2P^0$ multiplet in function of T[K]. Theoretical calculations: W$_{DDCS1}$ – present values for transition $S_{1/2}$–$P^0_{1/2}$; W$_{DDCS2}$ – present values for transition $S_{1/2}$–$P^0_{3/2}$; WT$_{NF}$ – N'Dollo & Fabry (1987). Experimental data: WE$_{NF}$ – N'Dollo & Fabry (1987).

N'Dollo & Fabry (1987) calculated Stark widths for four Ga I multiplets (Ga I $4p^2P^0$–$5s^2S$, $5s^2S$–$6p^2P^0$, $5s^2S$–$7p^2P^0$ and $5p^2P^0$–$10s^2S$) using the semiclassical theory of Griem et al. (1962) for the electron contribution and the quasistatic theory (Griem 1974) for ion contribution. They also obtained experimentally, observing spectroscopically a potassium-gallium arc, Stark widths for Ga I $4p^2P^0_{1/2}$–$5s^2S_{1/2}$ 4034.1 Å and $4p^2P^0_{3/2}$–$5s^2S_{1/2}$ 4173.2 Å spectral lines. A potassium-gallium mixture was used as the cathode, while the plasma was initiated in the presence of argon. In Figs. 1–3, our results are compared with experimental and theoretical results of N'Dollo & Fabry (1987). One can see that both calculations are in agreement with experimental data within the error bars. However, the temperature trend obtained by us diverges condiderably from the N'Dollo & Fabry (1987) result. In N'Dollo & Fabry (1987), the ion broadening contribution has been estimated within Griem's quasistatic approach (Griem 1974), and comparing calculated values in N'Dollo & Fabry (1987) with electron broadening and with electron + ion broadening. Within this approach the obtained contribution of ion broadening is negligible. However, if the impact approximation is valid, the result is different.

Since ionization potentials of Ga, K and Ar are 6.00 eV, 4.339 eV and 15.755 eV respectively, the most appropriate way to estimate the influence of ion-impact broadening for the considered experiment is to compare electron-impact widths with widths due to impacts with ions of the electron donors potassium and gallium. We obtained that the ion contribution is

Table 1. Electron-, proton- and He II-impact broadening parameters for Ga I for perturber density of 10^{14} cm^{-3} and temperatures from 2500 up to 50 000 K. Transitions and wavelengths (λ in Å) are also given in the table. By dividing C by the corresponding full width at half maximum (Dimitrijević et al. 1991), we obtain an estimate for the maximum perturber density for which the line may be treated as isolated and tabulated data may be used. The validity of the impact approximation has been estimated for data shown in this table, by checking if the collision volume (V) multiplied by the perturber density (N) is much less than one (Sahal-Bréchot 1969a,b).

Perturber density is 1.E+14 cm^{-3}					
Perturbers are:		Electrons		Protons	
Transition	T(K)	Width(Å)	Shift(Å)	Width(Å)	Shift(Å)
Ga I 4p^{2}P^0–5s^{2}S	2500.	0.173E−03	0.142E−03	0.438E−04	0.400E−04
	5000.	0.204E−03	0.166E−03	0.488E−04	0.450E−04
4125.8 A	10 000.	0.236E−03	0.196E−03	0.546E−04	0.506E−04
C = 0.14E+18	20 000.	0.257E−03	0.223E−03	0.610E−04	0.569E−04
	30 000.	0.268E−03	0.209E−03	0.652E−04	0.608E−04
	50 000.	0.287E−03	0.204E−03	0.708E−04	0.662E−04
Ga I 4p^{2}P^0–4d^{2}D	2500.	0.311E−03	−0.181E−03	0.757E−04	−0.452E−04
	5000.	0.311E−03	−0.176E−03	0.793E−04	−0.509E−04
2921.0 A	10 000.	0.315E−03	−0.163E−03	0.838E−04	−0.572E−04
C = 0.14E+17	20 000.	0.330E−03	−0.129E−03	0.894E−04	−0.644E−04
	30 000.	0.339E−03	−0.117E−03	0.933E−04	−0.689E−04
	50 000.	0.341E−03	−0.988E−04	0.990E−04	−0.751E−04
Ga I 4p^{2}P^0–5d^{2}D	2500.	0.124E−02	−0.762E−03	0.297E−03	−0.221E−03
	5000.	0.128E−02	−0.678E−03	0.322E−03	−0.251E−03
2484.0 A	10 000.	0.135E−02	−0.496E−03	0.351E−03	−0.285E−03
C = 0.25E+16	20 000.	0.140E−02	−0.375E−03	0.386E−03	−0.321E−03
	30 000.	0.138E−02	−0.303E−03	0.410E−03	−0.343E−03
	50 000.	0.135E−02	−0.219E−03	0.445E−03	−0.375E−03
Ga I 5s^{2}S–5p^{2}P^0	2500.	0.504E−02	0.368E−02	0.170E−02	0.954E−03
	5000.	0.581E−02	0.339E−02	0.177E−02	0.107E−02
12005.6 A	10 000.	0.696E−02	0.268E−02	0.186E−02	0.121E−02
C = 0.24E+18	20 000.	0.889E−02	0.155E−02	0.197E−02	0.136E−02
	30 000.	0.100E−01	0.105E−02	0.205E−02	0.146E−02
	50 000.	0.112E−01	0.508E−03	0.216E−02	0.159E−02
Ga I 5s^{2}S$_{1/2}$–6p^{2}P$^0_{1/2}$	2500.	0.110E−01	0.808E−02	0.273E−02	0.210E−02
	5000.	0.119E−01	0.818E−02	0.297E−02	0.239E−02
6415.2 A	10 000.	0.126E−01	0.732E−02	0.326E−02	0.271E−02
C = 0.18E+17	20 000.	0.136E−01	0.555E−02	0.359E−02	0.305E−02
	30 000.	0.141E−01	0.464E−02	0.382E−02	0.327E−02
	50 000.	0.144E−01	0.363E−02	0.414E−02	0.357E−02
Ga I 5s^{2}S$_{1/2}$–6p^{2}P$^0_{3/2}$	2500.	0.117E−01	0.855E−02	0.286E−02	0.223E−02
	5000.	0.125E−01	0.854E−02	0.313E−02	0.254E−02
6398.3 A	10 000.	0.133E−01	0.754E−02	0.344E−02	0.289E−02
C = 0.16E+17	20 000.	0.142E−01	0.573E−02	0.380E−02	0.326E−02
	30 000.	0.146E−01	0.476E−02	0.404E−02	0.349E−02
	50 000.	0.148E−01	0.369E−02	0.439E−02	0.381E−02
Ga I 5s^{2}S$_{1/2}$–7p^{2}P$^0_{1/2}$	2500.	0.311E−01	0.216E−01	0.732E−02	0.591E−02
	5000.	0.324E−01	0.198E−01	0.811E−02	0.684E−02
5361.3 A	10 000.	0.338E−01	0.163E−01	0.903E−02	0.783E−02
C = 0.40E+16	20 000.	0.344E−01	0.124E−01	0.101E−01	0.890E−02
	30 000.	0.341E−01	0.994E−02	0.109E−01	0.957E−02
	50 000.	0.333E−01	0.694E−02	0.119E−01	0.105E−01

around 20 per cent. N'Dollo & Fabry (1987) obtained their result for electron densities between 10^{14} cm^{-3} and 2×10^{15} cm^{-3} and scaled and presented them on 10^{16} cm^{-3}, where the impact approximation is not valid. However, since for some experimental densities this approximation is valid, the ion broadening contribution is probably underestimated.

Table 1. continued.

Perturber density is 1.E+14 cm^{-3}					
Perturbers are:		Electrons		Protons	
Transition	T(K)	Width(Å)	Shift(Å)	Width(Å)	Shift(Å)
Ga I 5s^{2}S$_{1/2}$–7p^{2}P$^0_{3/2}$	2500.	0.375E−01	0.248E−01	0.898E−02	0.735E−02
	5000.	0.390E−01	0.216E−01	0.100E−01	0.855E−02
5349.6 A	10 000.	0.399E−01	0.175E−01	0.112E−01	0.981E−02
C = 0.28E+16	20 000.	0.391E−01	0.129E−01	0.126E−01	0.112E−01
	30 000.	0.382E−01	0.102E−01	0.136E−01	0.120E−01
	50 000.	0.368E−01	0.693E−02	0.151E−01	0.132E−01
Ga I 5p^{2}P^0–5d^{2}D	2500.	0.419E−01	−0.259E−01	0.914E−02	−0.688E−02
	5000.	0.450E−01	−0.263E−01	0.992E−02	−0.782E−02
13004.3 A	10 000.	0.479E−01	−0.241E−01	0.108E−01	−0.886E−02
C = 0.68E+17	20 000.	0.500E−01	−0.202E−01	0.119E−01	−0.999E−02
	30 000.	0.507E−01	−0.175E−01	0.127E−01	−0.107E−01
	50 000.	0.509E−01	−0.143E−01	0.138E−01	−0.117E−01
Ga I 4d^{2}D–5p^{2}P^0	2500.	0.253	0.147	0.608E−01	0.389E−01
	5000.	0.284	0.168	0.642E−01	0.440E−01
59974.3 A	10 000.	0.308	0.175	0.685E−01	0.496E−01
C = 0.60E+19	20 000.	0.327	0.161	0.736E−01	0.558E−01
	30 000.	0.338	0.144	0.772E−01	0.597E−01
	50 000.	0.351	0.122	0.823E−01	0.651E−01
Ga I 4d^{2}D–6p^{2}P$^0_{1/2}$	2500.	0.946E−01	0.649E−01	0.220E−01	0.168E−01
	5000.	0.103	0.681E−01	0.239E−01	0.192E−01
17885.8 A	10 000.	0.110	0.639E−01	0.262E−01	0.217E−01
C = 0.14E+18	20 000.	0.115	0.542E−01	0.289E−01	0.245E−01
	30 000.	0.117	0.467E−01	0.307E−01	0.263E−01
	50 000.	0.118	0.365E−01	0.333E−01	0.287E−01
Ga I 4d^{2}D–6p^{2}P$^0_{3/2}$	2500.	0.990E−01	0.678E−01	0.228E−01	0.177E−01
	5000.	0.107	0.701E−01	0.249E−01	0.202E−01
17754.4 A	10 000.	0.114	0.647E−01	0.273E−01	0.229E−01
C = 0.12E+18	20 000.	0.119	0.544E−01	0.302E−01	0.258E−01
	30 000.	0.120	0.465E−01	0.321E−01	0.277E−01
	50 000.	0.121	0.360E−01	0.349E−01	0.302E−01
Ga I 4d^{2}D–7p^{2}P$^0_{1/2}$	2500.	0.148	0.100	0.342E−01	0.275E−01
	5000.	0.154	0.908E−01	0.378E−01	0.319E−01
11553.5 A	10 000.	0.161	0.733E−01	0.421E−01	0.365E−01
C = 0.18E+17	20 000.	0.163	0.506E−01	0.472E−01	0.415E−01
	30 000.	0.162	0.364E−01	0.507E−01	0.446E−01
	50 000.	0.157	0.268E−01	0.557E−01	0.488E−01
Ga I 4d^{2}D–7p^{2}P$^0_{3/2}$	2500.	0.177	0.114	0.416E−01	0.341E−01
	5000.	0.184	0.970E−01	0.464E−01	0.396E−01
11499.2 A	10 000.	0.188	0.766E−01	0.519E−01	0.454E−01
C = 0.13E+17	20 000.	0.184	0.511E−01	0.586E−01	0.517E−01
	30 000.	0.180	0.344E−01	0.632E−01	0.556E−01
	50 000.	0.173	0.257E−01	0.701E−01	0.610E−01
Ga I 5d^{2}D–6p^{2}P$^0_{1/2}$	2500.	24.0	14.7	4.83	3.68
	5000.	26.0	14.6	5.26	4.20
231830.3 A	10 000.	27.3	13.2	5.77	4.77
C = 0.22E+20	20 000.	28.7	10.0	6.38	5.39
	30 000.	29.3	8.31	6.79	5.78
	50 000.	29.3	6.75	7.38	6.31

Table 1. continued.

Perturber density is 1.E+14 cm^{-3}					
Perturbers are:		Electrons		Protons	
Transition	T(K)	Width(Å)	Shift(Å)	Width(Å)	Shift(Å)
Ga I $5d^2D$–$6p^2P^0_{3/2}$	2500.	30.6	18.8	6.12	4.70
	5000.	33.0	18.5	6.68	5.37
256416.8 A	10 000.	34.6	16.5	7.33	6.10
C = 0.26E+20	20 000.	36.2	12.5	8.11	6.90
	30 000.	36.8	10.3	8.64	7.40
	50 000.	36.7	8.25	9.42	8.07
Ga I $5d^2D$–$7p^2P^0_{1/2}$	2500.	1.81	1.15	0.385	0.309
	5000.	1.91	1.08	0.427	0.358
37979.6 A	10 000.	1.99	0.890	0.475	0.410
C = 0.20E+18	20 000.	2.02	0.624	0.532	0.466
	30 000.	2.00	0.491	0.571	0.501
	50 000.	1.95	0.336	0.628	0.548
Ga I $5d^2D$–$7p^2P^0_{3/2}$	2500.	2.08	1.30	0.454	0.370
	5000.	2.18	1.14	0.506	0.430
37398.7 A	10 000.	2.23	0.917	0.566	0.494
C = 0.14E+18	20 000.	2.19	0.620	0.639	0.562
	30 000.	2.15	0.486	0.689	0.605
	50 000.	2.07	0.310	0.764	0.663

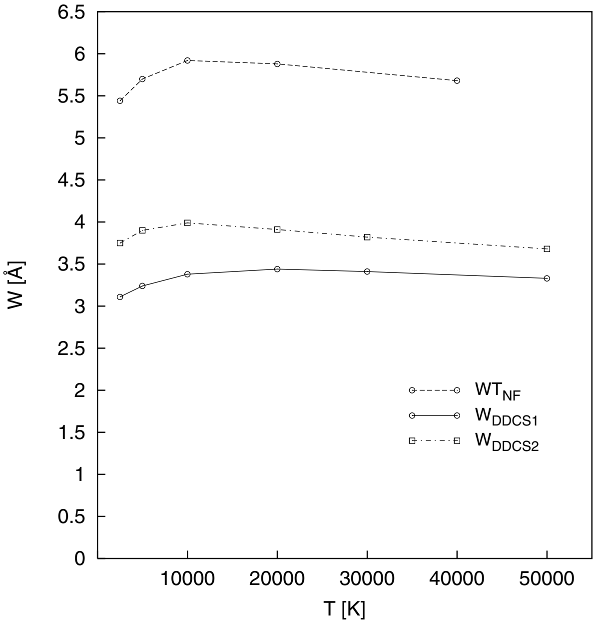

Fig. 3. Stark full widths at half maximum W[Å] for Ga I $5s^2S$–$7p^2P^0$ multiplet in function of T[K]. Theoretical calculations: W_{DDCS1} – present values for transition $S_{1/2}$–$P^0_{1/2}$; W_{DDCS2} – present values for transition $S_{1/2}$–$P^0_{3/2}$; WT_{NF} – N'Dollo & Fabry (1987).

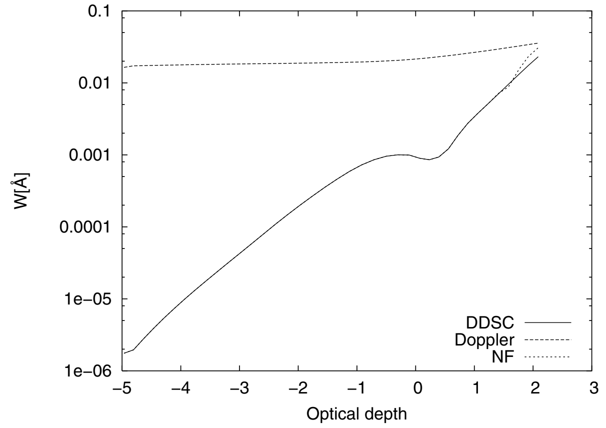

Fig. 4. Thermal Doppler and Stark widths for for Ga I $4p^2P^0$–$5s^2S$ multiplet as functions of optical depth for an A type star ($T_{\rm eff}$ = 10 000 K, log g = 4). Theoretical Stark line width calculations: DDCS – present work; NF – N'Dollo & Fabry (1987).

Lakićević (1983) estimated Stark broadening parameters for Ga I $4p^2P^0$–$5s^2S$ multiplet on the basis of regularities and systematic trends and he obtained that W is 0.30 Å and the absolute value of the shift 0.16 Å for an electron density of 10^{17} cm^{-3} and T = 20 000 K. Our width value is 0.257 Å and the shift value is 0.223 Å which is, taking into account the simplicity of the method, excellent for the width and within error bars for the shift.

To see the influence of the Stark broadening mechanism for Ga I spectral lines in stellar plasma conditions, we have calculated for our and N'Dollo & Fabry (1987) results included in Figs. 1–3 the Stark widths for a Kurucz's (1979). A type star ($T_{\rm eff}$ = 10 000 K, log g = 4) atmosphere model and compared them with Doppler ones. Results obtained as a function of the Rosseland optical depth are presented in Figs. 4–6. One can see that photospheric layers exist where Doppler and Stark widths are comparable and where the Stark width is dominant which is

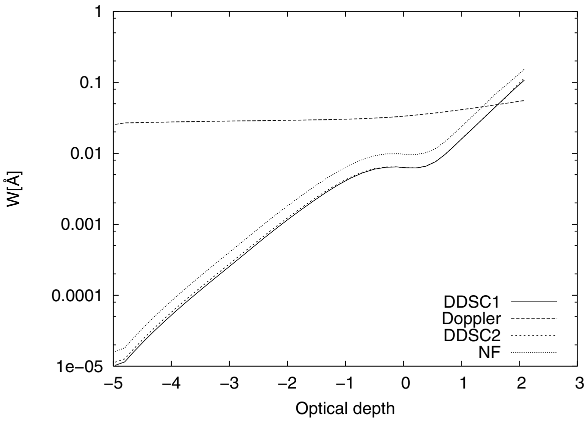

Fig. 5. Thermal Doppler and Stark widths for for Ga I $5s^2S$–$6p^2P^0$ multiplet as functions of optical depth for an A type star ($T_{\rm eff}$ = 10 000 K, log g = 4). Theoretical Stark line width calculations: DDCS1 – present values for transition $S_{1/2}$–$P^0_{1/2}$; DDCS2 – present values for transition $S_{1/2}$–$P^0_{3/2}$; NF – N'Dollo & Fabry (1987).

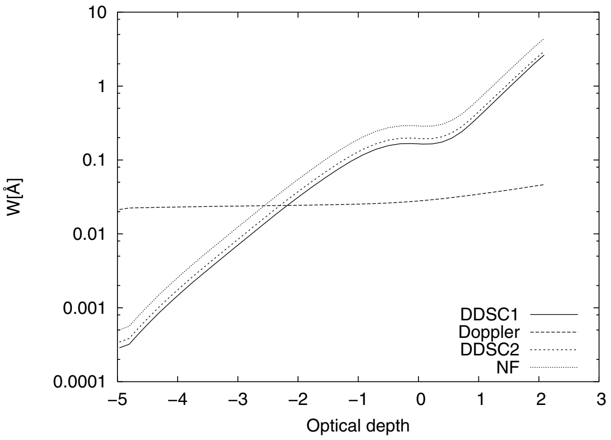

Fig. 6. Thermal Doppler and Stark widths for for Ga I $5s^2S$–$7p^2P^0$ multiplet as functions of optical depth for an A type star ($T_{\rm eff}$ = 10 000 K, log g = 4). Theoretical Stark line width calculations: DDCS1 – present values for transition $S_{1/2}$–$P^0_{1/2}$; DDCS2 – present values for transition $S_{1/2}$–$P^0_{3/2}$; NF – N'Dollo & Fabry (1987).

of interest when for example the stratification of gallium across the stellar photosphere is considered. Also, one can see that for transitions involving energy levels with higher principal quantum numbers, the importance of the Stark broadening mechanism increases. This increase is well illustrated in Figs. 5 and 6, where two members of the same spectral series, Ga I $5s^2S$–$6p^2P^0$ and $5s^2S$–$7p^2P^0$ are shown. This is due to the fact that with the increase of the principal quantum number of the upper level of the transition, the difference between this and the closest perturbing energy level decreases, resulting in the increase of the Stark broadening influence.

The new experimental evaluations of the Stark broadening parameters for Ga I spectral lines, especially at higher temperatures, will be of interest not only from the theoretical point of view but also for astrophysical and laboratory plasma diagnostics and modeling.

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