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On the Stark broadening of Co II spectral lines

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Stark full widths at half maximum for 12 Co II multiplets have been calculated using modified semiempirical method. The obtained results have been also used to demonstrate the importance of Stark broadening mechanism in DB white dwarfs.

Keywords: Quasars: emission lines – galaxies: starburst – quasars: supermassive black holes

1 Introduction

Spectral lines of singly charged cobalt ion (Co II) are present in stellar spectra. Such lines, for example, have been observed in Hg–Mn stars (see e.g. Bolcal and Didelon 1987), where Stark broadening is the principal pressure broadening mechanism. For Co II lines, which are needed for cobalt abundance determination, radiative transfer calculation and also for analysis and synthesis of stellar spectra, experimental or theoretical Stark broadening data do not exist in literature. It should be noticed, however, that the accurate determination of elementary abundance has a particular importance in astronomical spectroscopy, since the cosmic objects with relative abundance of elements different from those in usual stellar spectra measured from normal stars have been discovered. The main characteristic of these, chemically peculiar (CP) stars is anomalously strong or weak absorption lines in their spectra (Preston 1974), so the investigations of those spectra are of particular interest for the modelling of CP star atmospheres and stellar evolution in general. The special part of these investigations is spectral measurement and line shape modelling in spectra where transition metal ions, such as singly ionized cobalt, are observed. The spectral lines for Co II are present, for example, in most of the CP subclass of Hg–Mn stars, the atmospheres of which consist of greater or smaller concentration of Hg and/or Mn than the other stars which can be found lying in the main sequence of HR diagram. The investigations

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show persistence of large cobalt deficiency in the atmospheres of those objects, with metallicity of the order of 2 dex (Smith and Dworetzky 1993). The "singly ionized" stage dominates in spectrum of transition elements in the atmospheres of stars of spectral classes B–G, and it is especially found to be true for iron group of elements measuring ultraviolet region of spectra (Johansson 1995).

The first spectrum analysis of Co II was by Meggers (1928), who measured the spectrum between 2150 and 5000 Å, and identified 14 lines belonging to eight multiplets of Co II in the solar spectrum. The analysis was extended by Findlay (1930), Hagar (1951), Velasco and Adames (1966) and by Iglesias (1972, 1979). Iglesias commented that of the second spectra of the iron group elements one of the most incompletely known spectra was that of Co II. The compilations of energy levels of Co II from more recent times which are used also in our calculations are from Sugar and Corliss (1985) and Pickering et al. (1998). Pickering recorded high-resolution spectra of singly ionized cobalt by Fourier transform spectrometry in the region 1420–33333 Å with cobalt–neon and cobalt–argon hollow cathode lamp as a source (Pickering 1998, Pickering et al. 1998) and thus additionally contributed to the knowledge of these complex spectra being completed.

Stark broadening is usually the most important mechanism of spectral line broadening in high temperature and density plasma conditions. Collisions of emitters and absorbers with charged particles have an influence on spectral line shapes of stellar plasma, since splitting and shifting of atomic energy levels in electric field cause broadening and shifting lines in spectra. Therefore, any spectral line shape modelling of hot star spectra without including Stark broadening parameter calculations could cause the errors of abundance determination (see Popović et al. 2001, for example). It is also interesting to investigate the influence of Stark broadening on spectra of white dwarf atmospheres, where pressure and ionized matter concentration are high, so that the pressure mechanism of broadening could dominate over the thermal broadening in those spectra.

In this work we calculated Stark width parameters for spectral lines of Co II not existing until now, determined by using modified semiempirical theory (Dimitrijević and Konjević 1980), with hope that the results will be useful for astronomical purposes, as well as in spectral line shape modelling of laboratory plasma.

2 Methods of calculation

In order to analyze the UV and optical AGN spectral properties, we need to decompose spectral features and to obtain the emission which is coming from different emission regions. For that purpose, we made a model of the continuum and line decomposition. Here we present the Balmer continuum model, and optical and UV Fe II templates.

The Modified Semiempirical Method (MSE) is an improvement of the simple semiempirical method formulated by Griem (1968). It is different from Griem's semiempirical theory in that MSE calculates only the matrix elements of transitions for $\Delta n = 0$, while transitions elements for $\Delta n \neq 0$ are separately estimated and lumped together. This simplification accelerates the calculations and compared with some other approaches for obtaining Stark width and shift values, such as the semiempirical method of Griem (1968) or the semiclassical perturbation method of Sahal-Bréchot

(1969a, b), less atomic data is needed for calculations, so the usefulness of this approximative method arises when the set of data, necessary for the adequate use of other methods, is missing.

MSE has been tested and confirmed many times, in the last several decades, on many spectral lines of ions and neutrals calculating their Stark widths. Despite the theoretically predicted accuracy which is around ±50 %, it is found that even in the cases of emitters with very complex spectrum, such as Xe II and Kr II, this method gives relatively good agreement with experiments, with an accuracy of often better than ±30 % (Popović and Dimitrijević 1996, 1998; Kochukhov et al. 2006).

The required matrix elements are obtained from the Coulomb approximation theory of Bates and Damgaard (1949), while the line and multiplet factors are taken, whenever it is necessary, from Shore and Menzel (1968). During all calculations we assumed that all conditions for the validity of MSE approach were satisfied, e.g. plasma ideality, impact approximation, non-overlapping spectral lines, etc. (see for example Milovanović 2004 or Milovanović et al. 2005). The energy levels used to calculate electron-impact broadening parameters of spectral lines are from Sugar and Corliss (1985). They are originally observed and determined by Pickering (1998) and Pickering et al. (1998), and they are also in the NIST Atomic Spectra Database, http://physics.nist.gov/asd (Kramida et al. 2015). Since the so-called one-electron approximation can be applied, the energy levels are averaged over the quantum number J before calculations.

3 Results and discussion

Stark widths (FWHM, Full Widths at Half intensity Maximum) for 12 Co II spectral lines, calculated in this work by MSE formalism are presented in Table 1. Stark widths from this paper will enter in the STARK-B database (http://stark-b.obspm.fr/ – Sahal-Bréchot et al. (2014, 2015a,b)), which is a part of Virtual Atomic and Molecular Data Center (VAMDC – http://vamdc.org/ Dubernet et al., 2010) and also has a link in Serbian Virtual Observatory (http://servo.aob.rs/ – Jevremović et al. (2009), Dimitrijević et al. (2011)).

Results from Table 1 are used to find their fitting relation to temperature according to results from Sahal-Bréchot et al. (2011) about temperature dependence of Stark widths. The fitting parameters are given in Table 2. And finally, we simulated the conditions in DB white dwarf atmosphere using appropriate model atmosphere (Wickramasinghe 1972) to show the importance of Stark broadening influence on spectral line shape in the spectrum of a DB white dwarf. Such an investigation has been already performed in the case of Co III spectral lines, with conclusion of Stark broadening domination related to Doppler broadening in practically all relevant atmospheric layers of DA, DO, or DB white dwarf atmospheres (Tankosić et al. 2003). In Fig. 1 the comparison of Stark widths and Doppler widths of the same Co II spectral line as a function of the optical depth in the white dwarf atmosphere is shown as an example, so that one can see in which layers of stellar atmosphere Doppler broadening caused by thermal motion of particles is overdominated by Stark broadening. But even in the layers where this is not the case, the effect of Stark broadening can still influence the shape of spectral line wings.

Table 1 MSE Stark FWHM widths (WMSE) calculated for transitions of Co II, each for five different temperature values. Electron density of 10^{23} m^{-3} is used.

Transition	T (K)	W (Å)
	10000	0.3554E-01
(^{2}G)4s a^{3}G–(^{2}G)4p y^{3}F^0	20000	0.2513E-01
2370.0	50000	0.1589E-01
	100000	0.1144E-01
	200000	0.9291E-02
	10000	0.3747E-01
(^{2}G)4s a^{3}G–(^{2}G)4p y^{3}G^0	20000	0.2650E-01
2326.8	50000	0.1676E-01
	100000	0.1207E-01
	200000	0.9930E-02
	10000	0.4262E-01
(^{2}G)4s a^{3}G–(^{2}G)4p y^{3}H^0	20000	0.3013E-01
2404.1	50000	0.1906E-01
	100000	0.1381E-01
	200000	0.1143E-01
	10000	0.3929E-01
(^{2}G)4s b^{1}G–(^{2}G)4p y^{3}F^0	20000	0.2778E-01
2446.8	50000	0.1757E-01
	100000	0.1269E-01
	200000	0.1042E-01
	10000	0.4600E-01
(^{2}G)4s b^{1}G–(^{2}G)4p y^{3}G^0	20000	0.3253E-01
2547.5	50000	0.2057E-01
	100000	0.1497E-01
	200000	0.1245E-01
	10000	0.4821E-01
(^{2}G)4s b^{1}G–(^{2}G)4p y^{3}H^0	20000	0.3409E-01
2511.9	50000	0.2156E-01
	100000	0.1571E-01
	200000	0.1318E-01
	10000	0.3321E-01
(^{2}D2)4s b^{1}D–(^{2}D2)4p y^{1}P^0	20000	0.2348E-01
2308.2	50000	0.1485E-01
	100000	0.1065E-01
	200000	0.8715E-02
	10000	0.4152E-01
(^{2}D2)4s b^{1}D–(^{2}D2)4p y^{1}D^0	20000	0.2936E-01
2412.3	50000	0.1857E-01
	100000	0.1343E-01
	200000	0.1113E-01
	10000	0.4747E-01
(^{2}D2)4s b^{1}D–(^{2}D2)4p y^{1}F^0	20000	0.3357E-01
2419.2	50000	0.2123E-01
	100000	0.1543E-01
	200000	0.1296E-01

Table 1 (continued)

Transition	T (K)	W (Å)
	10000	0.3049E-01
(^{2}D2)4s a^{3}D–(^{2}D2)4p x^{1}P^0	20000	0.2156E-01
2251.8	50000	0.1364E-01
	100000	0.9756E-02
	200000	0.7906E-02
	10000	0.4014E-01
(^{2}D2)4s a^{3}D–(^{2}D2)4p x^{1}D^0	20000	0.2838E-01
2424.0	50000	0.1795E-01
	100000	0.1298E-01
	200000	0.1065E-01
	10000	0.4354E-01
(^{2}D2)4s a^{3}D–(^{2}D2)4p x^{1}F^0	20000	0.3079E-01
2360.4	50000	0.1947E-01
	100000	0.1410E-01
	200000	0.1175E-01

Table 2 Calculated values of Stark widths are used to find approximative formula of their dependence on temperature (Sahal-Bréchot et al. 2011): $\log w(T) = a + b \log T + c \log^2 T$. Parameters a, b and c are tabulated here.

Transition	a	b	c
(^{2}G)4s a^{3}G–(^{2}G)4p y^{3}F^0 2370.0	2.3203316	–1.3063933	0.091330817
(^{2}G)4s a^{3}G–(^{2}G)4p y^{3}G^0 2326.8	2.4958303	–1.3758090	0.099183671
(^{2}G)4s a^{3}G–(^{2}G)4p y^{3}H^0 2404.1	2.6621798	–1.4271676	0.105128930
(^{2}G)4s b^{1}G–(^{2}G)4p y^{3}F^0 2446.8	2.5129190	–1.3747688	0.099134218
(^{2}G)4s b^{1}G–(^{2}G)4p y^{3}G^0 2547.5	2.7772013	–1.4652067	0.109532050
(^{2}G)4s b^{1}G–(^{2}G)4p y^{3}H^0 2511.9	2.9094457	–1.5162555	0.115322570
(^{2}D2)4s b^{1}D - (^{2}D2)4p y^{1}P^0 2308.2	2.3594482	–1.3367037	0.094644720
(^{2}D2)4s b^{1}D–(^{2}D2)4p y^{1}D^0 2412.3	2.6537361	–1.4281066	0.105188370
(^{2}D2)4s b^{1}D–(^{2}D2)4p y^{1}F^0 2419.2	2.9011653	–1.5149979	0.115111830
(^{2}D2)4s a^{3}D–(^{2}D2)4p x^{1}P^0 2251.8	2.1855703	–1.2742824	0.087564569
(^{2}D2)4s a^{3}D–(^{2}D2)4p x^{1}D^0 2424.0	2.5200865	–1.3740665	0.099088264c
(^{2}D2)4s a^{3}D–(^{2}D2)4p x^{1}F^0 2360.4	2.7495962	–1.4624380	0.109083170

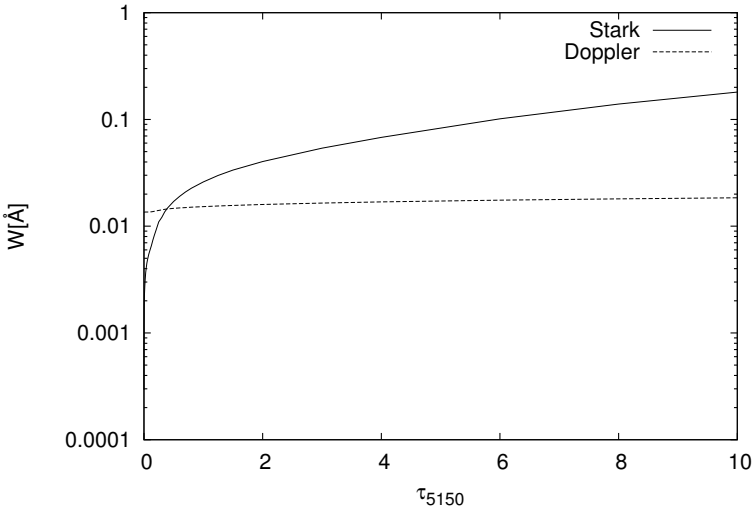


Figure 1 Stark and Doppler widths for Co II (^{2}G)4s a^{3}G – (^{2}G)4p y^{3}F^0 ($\lambda = 2370.0$ Å) spectral line as a function of optical depth (τ_{5150}). Stark and Doppler widths are shown for an atmospheric model with effective temperatures $T_{\rm eff} = 15000$ K, and $\log g = 8$.

We hope that the new Stark broadening data for Co II will be useful for various problems not only in astrophysics but also for laboratory plasma research, modelling and diagnostics.

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