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Stark broadening of spectral lines in chemically peculiar stars: Te I lines and recent calculations for trace elements

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ABSTRACT

With the development of astronomical observations from space, spectral lines of trace elements can now be observed in stellar spectra with good resolution, and atomic data for such atoms and ions have an increasing significance. We review here work in Belgrade on the influence of Stark broadening of trace elements on stellar spectra and present new determinations of Stark broadening parameters of neutral tellurium. Also the corresponding Stark and Doppler widths are compared in atmospheres of A type stars.

1. Introduction

Stark broadening of neutral atom and ion lines is of interest not only for laboratory, laser produced, fusion or technological plasma investigation but also for astrophysical plasma, particularly for synthesis and analysis of high-resolution spectra obtained from space born instruments.

With the development of new space techniques, importance of data on trace element spectra increases. The spectral lines of tellurium, one of the least abundant elements in the Earth's lithosphere, but with cosmic abundance larger than for any element with atomic number greater than 40 (Cohen, 1984), are observed in stellar spectra. For example, Yuschenko and Gopka (1996), identified one line of tellurium in the Procyon photosphere spectrum, and determined the abundance of this element as $\log N(\mathrm{Te}) = 3.04$ (in the scale $\log N(\mathrm{H}) = 12.00$). de Lester (1994) notes that the three s-only isotopes of tellurium Te-122, 123 and 124 provide a unique opportunity to investigate s-process systematics, and for the estimation of the temperature and neutron density during helium burning in red giant stars. Chayer et al. (2005) observed tellurium spectral lines in ultraviolet spectra of the cool DO white dwarf HD199499, obtained with the Far Ultraviolet Spectroscopy Explorer (FUSE), the Goddard High Resolution Spectrograph (GHRS – on the Hubble Space Telescope) and the International Ultraviolet Explorer. They report as well presence of tellurium lines in FUSE and GHRS spectra of the cool DO dwarf HZ21. Since the DO white dwarfs represent the non-DA white dwarf cooling sequence with effective temperatures from approximately 45,000 K up to around 120,000 K (Dreizler and Werner, 1996), Stark broadening is very important for analysis of their spectra. Consequently, the corresponding line broadening parameters for Te I at the low temperature limit (45,000–50,000 K) and tellurium in various ionization stages for the whole temperature range of interest for DO white dwarf atmospheres are needed.

Atomic data for other trace elements are also important. For example, chromium is one of the most peculiar elements in the atmospheres of magnetic chemically peculiar stars. Cr II lines were found for example in Alpha UMi (Polaris) and HR 7308 by Andrievsky et al. (1994). Spectral lines of Cu III are of particular interest for the diagnostics and modelling of plasma created in electromagnetic macro particle accelerators (see Rasheig and Marshall, 1978). Moreover, analysis of 11 spectra of HgMn stars (Jacobs and Dworetsky, 1981), where Stark broadening is the main pressure broadening mechanism, showed the clear presence of copper and even its overabundance in 10 of 11 investigated stars. Recently for example, copper abundances in a large sample of metal-poor

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stars have been investigated (Primas and Sobeck, 2008), and zinc spectral lines are also identified in stellar spectra (Adelman, 1994). Selenium, a trace element without previous astrophysical significance, is now detected in the atmospheres of cool DO white dwarfs (Chayer et al., 2005). Many examples show presence in hot stellar atmospheres of ionized manganese, gold, indium, tin, ruthenium, rare earths and other trace elements which before the epoch of space born stellar spectroscopy were astrophysically insignificant, but now the need for their atomic data is increasing.

High-resolution spectra allow us to study different broadening effects using well-resolved line profiles. Stark broadening is the most important pressure broadening mechanism for A type stars and especially for white dwarfs. Neglecting this mechanism may therefore introduce significant errors into abundance determinations and spectra modellisation.

Here we use the semiclassical perturbation method (Sahal-Bréchot, 1969a,b) to calculate the Stark broadening parameters for 4 Te I multiplets within the ultraviolet, visible and infrared wavelength range, for temperatures between 2500 K and 50,000 K. Within this range are temperatures of interest for A and B type stars and DA, DB and cool DO white dwarfs where Stark broadening is of interest. Such temperatures may be of interest also for the modelling of subphotospheric layers even in cooler stars. Results obtained will be used for analyzing the influence of Stark broadening in A type stellar atmospheres. Also a review of work performed in Belgrade on the investigations of Stark broadening influence in stellar spectra is given.

2. Theory

Calculations have been performed within the semiclassical perturbation formalism, developed and discussed in detail by Sahal-Bréchot (1969a,b). This formalism, as well as the corresponding computer code, has been optimized and updated several times (see e.g. Sahal-Bréchot, 1974; Dimitrijević and Sahal-Bréchot, 1984; Dimitrijević et al., 1991; see also review Dimitrijević, 1996).

Within this formalism, the full width of an isolated spectral line of a neutral emitter broadened by electron impact (W) can be expressed in terms of cross sections for elastic and inelastic processes as

$$W = \frac{\lambda^2}{\pi c} N \int v f(v) dv \left(\sum_{i' \neq i} \sigma_{ii'}(v) + \sum_{f' \neq f} \sigma_{ff'}(v) + \sigma_{el} + W_R \right), \tag{1}$$

and the corresponding line shift d as

$$d = \frac{\lambda^2}{2\pi c} N \int v f(v) dv \int_{R_3}^{R_D} 2\pi \rho d\rho \sin 2\phi_p \cdot s. \tag{2}$$

Here, λ is the wavelength of the line originating from the transition with initial atomic energy level i and final level f, c is the velocity of light, N is the electron density, $f(v)$ is the Maxwellian velocity distribution function for electrons, ρ denotes the impact parameter of the incoming electron, and ϕ_p is the phase shift due to the polarization potential. The inelastic cross sections $\sigma_{jj'}(v)$ (where $j = i$ or f) and elastic cross section σ_{el} are determined according to Chapter 3 in Sahal-Bréchot (1969b). The cut-offs (needed for the calculation of inelastic and elastic cross sections and the shift), included in order to maintain for the unitarity of the S-matrix, and to take into account Debye screening are described in Section 1 of Chapter 3 in Sahal-Bréchot (1969b). W_R gives the contribution of the Feshbach resonances (Fleurier et al., 1977) and this term is zero if the emitters are neutral atoms. Other differences between neutral and ionized emitters is that for calculations of the cross sections rectilinear perturber paths are taken for neutral ones and hyperbolic paths for ionized species.

The theoretical and computational differences between calculations performed by our group using the theory of Sahal-Bréchot (1969a,b) and semi-classical Stark broadening results given in Griem (1974) are explained in detail in Dimitrijević and Sahal-Bréchot (1996).

The formulae for the ion-impact broadening parameters are analogous to the formulae for electron-impact broadening. We note that the fact that the colliding ions could be treated using impact approximation in the far wings should be checked, even for stellar atmosphere densities.

It is possible also to perform calculations ab initio, using atomic energy levels and oscillator strengths calculated together with the Stark broadening parameters (Ben Nessib et al., 2004; Ben Nessib, 2009).

When the semiclassical perturbation formalism can not be applied in an adequate way, due to the lack of reliable atomic data, a modified semiempirical formalism has been used.

According to the modified semiempirical (MSE) approach (Dimitrijević and Konjević, 1980; Dimitrijević and Kršljanin, 1986, for review see Dimitrijević and Popović, 2001) the electron impact full width at half maximum (FHWM) of an isolated ion line is given by

$$\begin{aligned} W = {} & N \frac{4\pi}{3c} \frac{\hbar^2}{m^2} \left(\frac{2m}{\pi k T} \right)^{1/2} \frac{\lambda^2}{\sqrt{3}} \\ & \cdot \left\{ \sum_{\ell_i \pm 1} \sum_{L_{i'} J_{i'}} R^2_{\ell_i, \ell_i \pm 1} \tilde{g}(x_{\ell_i, \ell_i \pm 1}) + \sum_{\ell_f \pm 1} \sum_{L_{f'} J_{f'}} R^2_{\ell_f, \ell_f \pm 1} \tilde{g}(x_{\ell_f, \ell_f \pm 1}) \right. \\ & \left. + \left(\sum_{i'} R^2_{ii'} \right)_{\Delta n \neq 0} g(x_{n_i, n_i + 1}) + \left(\sum_{f'} R^2_{ff'} \right)_{\Delta n \neq 0} g(x_{n_f, n_f + 1}) \right\}, \end{aligned} \tag{3}$$

where n and ℓ are principal and angular momentum quantum numbers, and $R^2_{\ell_k, \ell_{k'}}$, $k = i, f$ is given by

$$\left(\sum_{k'} R^2_{kk'} \right)_{\Delta n \neq 0} = \left(\frac{3 n_k^*}{2Z} \right)^2 \frac{1}{9} \left(n_k^{*2} + 3\ell_k^2 + 3\ell_k + 11 \right), \tag{4}$$

in the Coulomb approximation.

In Eq. (3)

$$x_{\ell_k, \ell_{k'}} = E / \Delta E_{\ell_k, \ell_{k'}}, \tag{5}$$

$k = i, f$ where $E = \frac{3}{2} kT$ is the electron kinetic energy and

$$\Delta E_{\ell_k, \ell_{k'}} = \left| E_{\ell_k} - E_{\ell_{k'}} \right|, \tag{6}$$

is the energy difference between levels ℓ_k and $\ell_k \pm 1 (k = i, f)$. Also

$$x_{n_k, n_k + 1} \approx E / \Delta E_{n_k, n_k + 1}, \tag{7}$$

where for $\Delta n \neq 0$ the energy difference between energy levels with n_k and $n_k + 1$, $\Delta E_{n_k, n_k + 1}$, is estimated as

$$\Delta E_{n_k, n_k + 1} \approx 2 Z^2 E_H / n_k^{*3}. \tag{8}$$

In Eq. (4) the effective principal quantum number is defined by

$$n_k^* = [E_H Z^2 / (E_{ion} - E_k)]^{1/2}, \tag{9}$$

Z is the residual ionic charge i.e. the charge of the rest of atom as "seen" by optical electron (for example $Z = 1$ for neutral atoms, 2 for singly charged ions, etc.), and E_{ion} is the appropriate spectral series limit.

In Eq. (3) T is the electron temperature, while $g(x)$ (Griem, 1968) and $\tilde{g}(x)$ (Dimitrijević and Konjević, 1980) denote the corresponding effective Gaunt factors.

In comparison with the semiclassical perturbation approach (Sahal-Bréchot, 1969a,b), the modified semiempirical approach requires much less atomic input data. In fact, if there are not perturbing levels strongly violating the assumed approximation, we only