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STARK SHIFTS OF C IV LINES IN THE SPECTRUM OF PG 1159-035

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Abstract. Using the semiclassical results for electron- and proton-impact shifts as well as a NLTE model atmosphere, we have calculated total Stark shifts (due to collisions with electrons and He^{2+}, C^{4+}, O^{6+}, H^{+} ions, estimating the ionic contribution within the adiabatic approximation) of the cores of *C IV* lines from 62 multiplets in the spectrum of the carbon rich, very hot, pulsating pre White Dwarf PG 1159-035 (log g=7; T_{eff}=140,000 K; C/He=0.7, H/He=0.21 by number), prototype of its class. Obtained shifts vary for six orders of magnitude, reaching 80km/s for *6f–7g* multiplet.

1. Pressure and Stellar Spectral Line Shapes

Besides the important contribution to the widths of spectral lines in atmospheres of main sequence and high-gravity stars, collisions with neutral and charged particles are also cause of the shift (and asymmetry, due to the fact that each profile is formed in a thick atmospheric layer, with pressure and temperature variable with depth) of spectral lines. We have investigated in detail the contribution of the pressure broadening to the over-all asymmetries and shifts in the spectra of the Sun (e.g. Vince *et al.*, 1985; Kršljanin *et al.*, 1991) and of the hot stars (Kršljanin, 1989; Kršljanin & Dimitijević, 1992, Kršljanin & Marković-Kršljanin, 1992). Pressure contribution to the observed shifts is usually dominated and masked by thermal and different types of non-thermal motions in the stellar atmosphere, but in the case of "quiet" stellar atmospheres, accurate diagnostics of atmospheric motions would not be possible without knowledge of the reliable pressure broadening parameters.

Normal chemical composition of the stars rarely offer the possibility for the investigation of metallic lines with large principal quantum number, especially in high-gravity conditions (atmospheres of White Dwarfs are usually "purified" due to gravitational diffusion). The PG 1159 stars, with the combined strong chemical peculiarity, high gravity and very high temperatures, seem to be ideal objects for detailed investigation of Stark broadening contribution to the stellar spectral line shapes.

2. The Star: Atmospheric Properties and the Model

The PG 1159-035 was discovered in 1979 by McGraw *et al.* Its spectrum is characterized by a broad absorption trough due to *He II* 4686 and many neighbouring *C IV* lines, accompanied by central emission reversals (the emission does not exist in all stars of this type). Although the absence of *H* and *He I* absorption lines implied a hot, hydrogen deficient atmosphere, its chemical composition have been revealed only recently. Until now, 18 stars (Werner, 1992) of this type have been discovered (among them: 7 pulsators, 8 do not pulsate, 8 are the Central Stars of the Planetary Nebulae). PG 1159s are among the hottest stars known; with its atmospheres dominated by carbon and helium and with considerable amount of oxigen, they are defined as direct progenitors of DO White Dwarfs. Spectra of these stars show existence of very complex blends and no mass loss. Due to very high temperatures, precise chemical analysis of these stars requires highly sophysticated model atmospheres (line blanketed, NLTE, with real metal oppacities).

Here, for the prototype star, PG 1159-035 we have used a Kiel model atmosphere (Werner *et al.*, 1991; Rauch, 1991) constructed using the Axelerated Lambda Iteration tehnique, and with *H, He, C, N, O* atoms treated in detail (Fig. 1.). Adopted atmospheric parameters (due to best fit to the line spectra) are T_{eff} =140,000K, log g=7, with major abundances (by number): C/He=0.7, O/He=0.13, H/He=0.21 and with the traces of nitrogen. On the basis of this model, Rauch (1991) calculated formation depths of the cores of 96 *C IV* lines observed in PG 1159-035 spectrum, finding that they lay in the interval (-2.9 $<$ log m $<$ -1.4) - Fig.1.

As for the observed shifts, Wesemael *et al.* (1985) found that the centers of major absorption troughs (*He II* 4686, *C IV* 4658) are redshifted in comparison with narrow emission reversals. *C IV* 4441 is similarly shifted too. Amount of gass motions and gravity in these shifts is still uncertain.

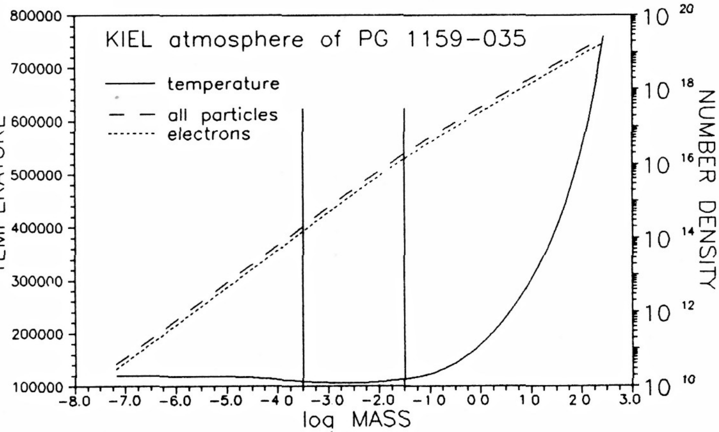

Fig.1. *NLTE model atmosphere of PG 1159-035. Region where cores of all examined C IV lines are formed is between two vertical lines (Rauch, 1991).*

3. Electron- vs. Ion-Impact Shifts

In a series of papers (see Dimitrijević & Sahal-Bréchot, 1993 and references therein) sets of Stark broadening parameters (electron-, proton-, and He^{+}-impact widths and shifts) of spectral lines of several multicharged ions of astrophysical interest are given. All these results were obtained by using the semiclassical-perturbation formalism (Sahal-Bréchot, 1969a,b). The most complete set of Stark widths and shifts is given for the *C IV* case (Dimitrijević *et al.*, 1991a,b; Dimitrijević & Sahal-Bréchot, 1992). It covers 62 of 96 lines observed and analyzed by Rauch (1991) in PG 1159-035. Although lot of lines with high principal quantum number are included, for ones with $n > 7$ (and $n > 9$ for l=s) it was not possible to obtain Stark broadening parameters of the same reliability.

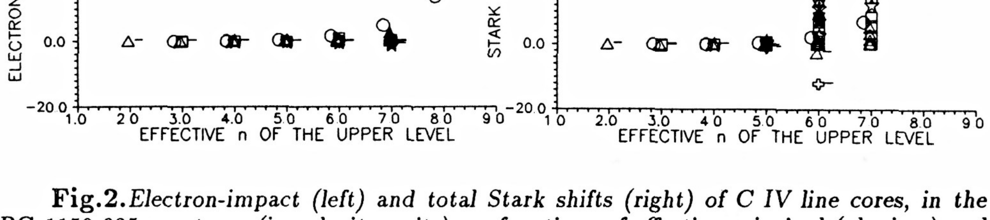

Fig.2. *Electron-impact (left) and total Stark shifts (right) of C IV line cores, in the PG 1159-035 spectrum (in velocity units), as functions of effective principal (abscissa) and orbital (explained in the legend) quantum numbers of the upper levels in transitions.*

In usual laboratory and stellar conditions ion-impact widths and shifts are only corrections to the electron-impact parameters. But in the case of PG 1159 stars, due to their chemical composition and temperatures, the contribution of ion-impact widths and shifts should be substantial, if not dominant. Ionization balance shows that impact contribution of C^{4+}, He^{2+}, O^{6+}, H^{+} and possibly O^{5+} ions should be taken into account. Starting from the consideration that when the impact approximation for the ionic perturbers is valid, the adiabatic approximation is also valid, one can expect that by using the adiabatic approximation, a certain scaling law may be found, that would allow us to estimate Stark shifts for all these ions as perturbers, starting from available semiclassical data on proton-impact shifts only. According to adiabatic theory of Lindholm and Foley (e.g. Kršljanin, 1989) Stark shifts (and widths) at a given temperature are proportional to $m^{-1/6}Z^{2/3}N$, where m is mass Z - charge, and N number density of the perturbers. Application of this scaling law in our case becomes trivial, since in the region where line cores are formed (Fig.1.) number densities of all most important ionic perturbers have the constant ratios one to each other and to electrons number density. Following this idea, one can obtain the estimate that the over-all ionic shift equals 13.63 times the proton-impact shift (contributions of the ionic species: He^{2+} - *44%*, C^{4+} - *41%*, H^{+} - *7%*, O^{6+} - *7%* and O^{5+} - *1%*).

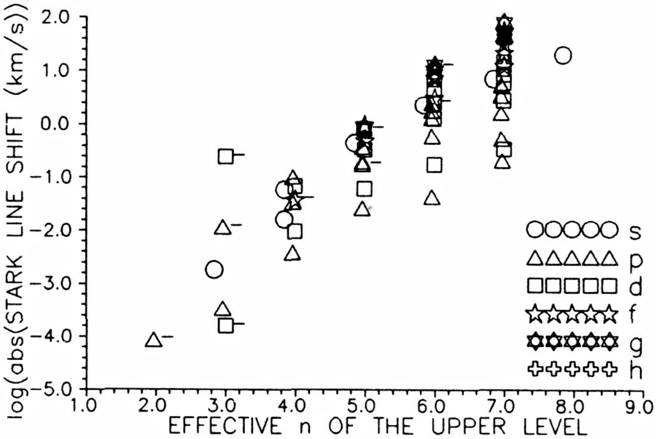

Fig.3. *Same as in Fig.2. but with shifts in a logarithmic scale. Negative (blue) shifts are denoted by minus signs.*

4. Shifted Stellar Line Cores: Results and Discussion

Calculated Stark shifts for 62 *C IV* lines in the atmosphere of PG 1159-035 are shown in Figs.2-5. as functions of their atomic parameters (effective principal and orbital quantum numbers of the upper levels in the transitions) and formation depths. A look into the numerical results shows the dominant role of the ion-impact broadening in most of the cases.

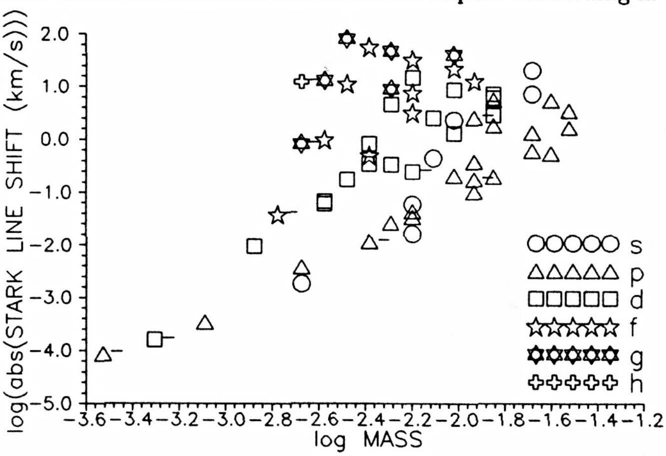

Fig.4. *Total Stark shifts of C IV line cores as function of their formation depths. Notation is the same as in Figs.2. and 3.*

For the transitions to *s* and *p* levels electronic and ionic contributions are of the same order of magnitude (for *s* transitions electrons slightly dominate; about 70% of the total Stark shifts are due to electron-impacts). For most of the *d* transitions electron-impact contribution is less than 10% and for *f* ones even less than 5% with opposite signs of electron and ion contributions as a rule. For transitions to *g* and *h* levels it seems that electron-impact contribution is negligible (we calculated shifts for 7 transitions to *s* levels, 21 to *p*, 17 to *d*, 10 to *f*, 6 to *g* and 1 to *h* level). Nine multiplets have blue total shifts and in 12 cases electron and ion contributions have the opposite signs. Least calculated shift is 9*cm/s* (*2s–2p* resonant multiplet) and the largest one is 80 *km/s* (*6f-7g*). Distribution of the total shift values is the following: shifts <10*m/s* have 6 lines, 10–100*m/s* 9 lines, 100–1000*m/s* 16 lines, 1–10*km/s* 19 lines and >10*km/s* 12 lines.

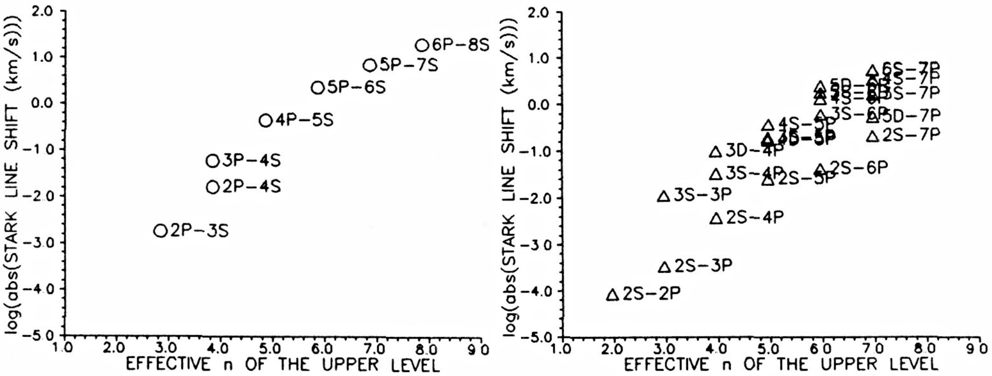

Fig.5. *Total Stark shifts of the cores of C IV lines with upper orbital quantum numbers s (left) and p (right). Notation is the same as in Figs.2. and 3.*

The figures show again the pronounced dependance of the stellar Stark shifts on the (effective) principal quantum number, especially regular within the spectral series. Substantial values of Stark shifts in PG 1159-035 predicted here suggest the need for more accurate calculation of widths and shifts due to collisions with He^{2+}, C^{4+} and O^{6+} ions, as well as the need for careful paralel analysis of theoretical and observed shifts.

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