Širenje spektralnih linija u atmosferama hemijski neobičnih zvezda i belih patuljaka

Dr Zoran Simić
Astronomska opservatorija Beograd

Uvod

Spektar

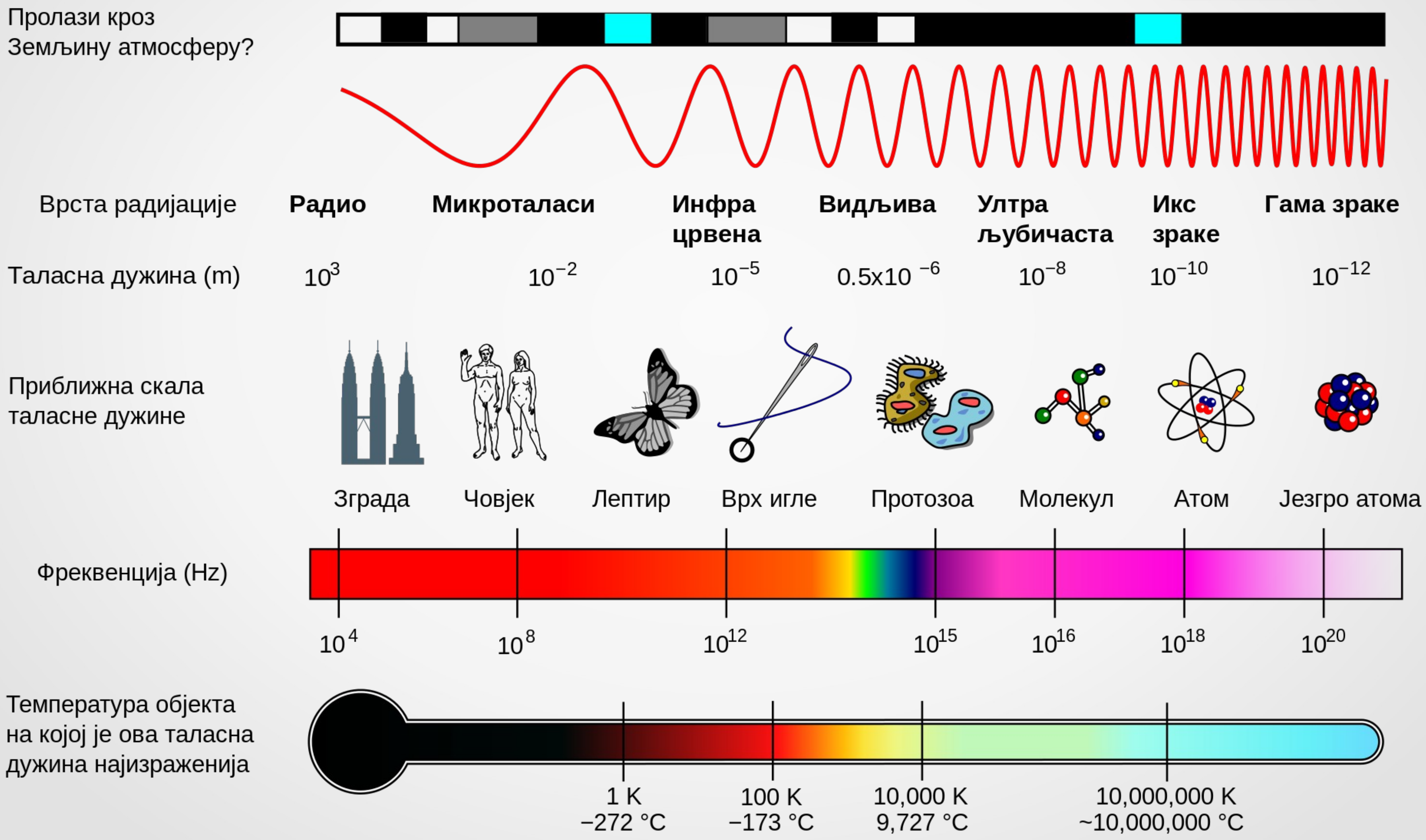
Spektralne linije

Plazma-stanje materije

Nova svemirska tehnologija

Chemically Peculiar Stars & White Dwarfs

Spektar - "spektar elektromagnetnog zračenja"

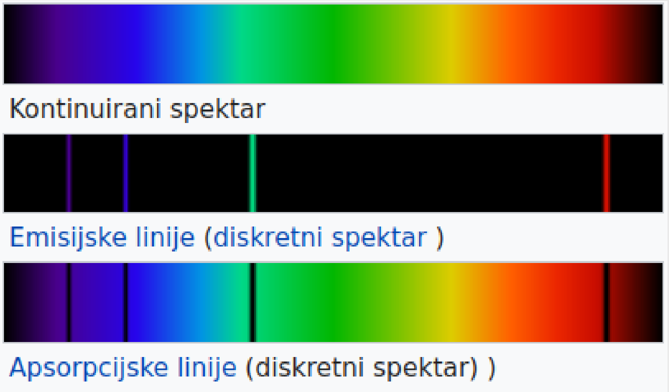


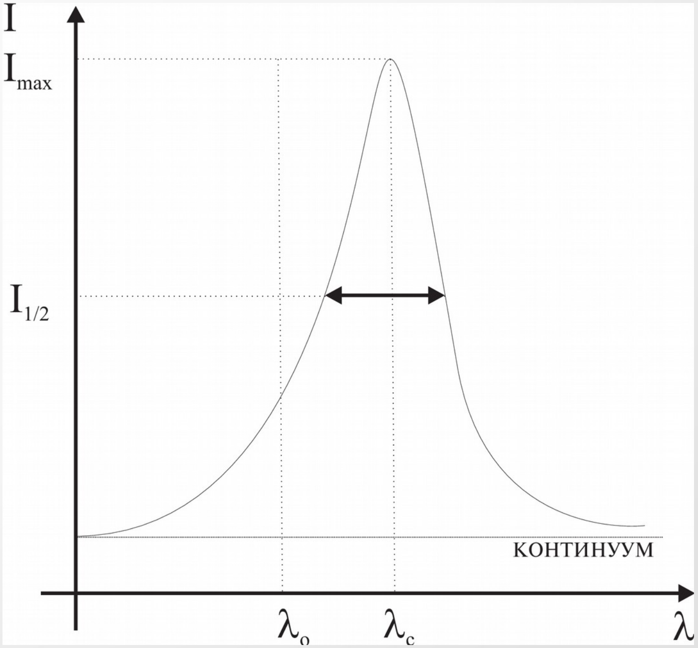
Spektralne linije

Interpretacija kompleksnog oblika spektralne linije moguća je ako postoji dobar opis fizičke slike procesa unutar atoma ili jona u kojima se odigravaju prelazi sa različitih energetskih nivoa.

Zvezdana atmosfera koja je u stanju plazme emituje zračenje koje formira spektralne linije odredjene širine. Centralni deo linije nastaje u višim slojevima atmosfere za razliku od krila.

Pri različitim uslovima u plazmi dolaze do izražaja različiti mehanizmi širenja profila spektralne linije. Za nas je od naročitog značaja Štarkovo širenje do koga dolazi pri interakciji emitera sa naelektrisanom česticom a koje je pored Doplerovog širenja često dominantan mehanizam koji utiče na širinu i oblik linije u plazmi. U električnom polju elektrona i jona plazme, energetski nivoi atoma koji emituje fotone se cepaju i pomeraju što je poznato kao Štarkov efekat.



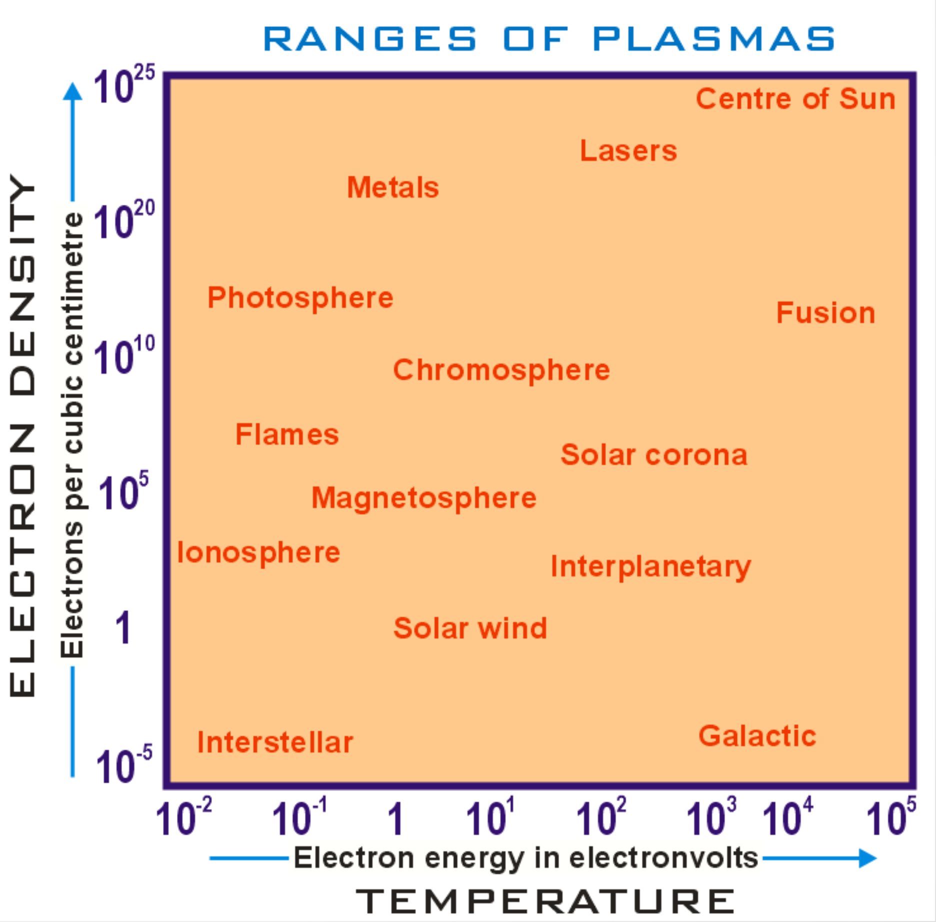


Plazma

-Zemaljska
-Tehnološka-LAB
-Astrofizička

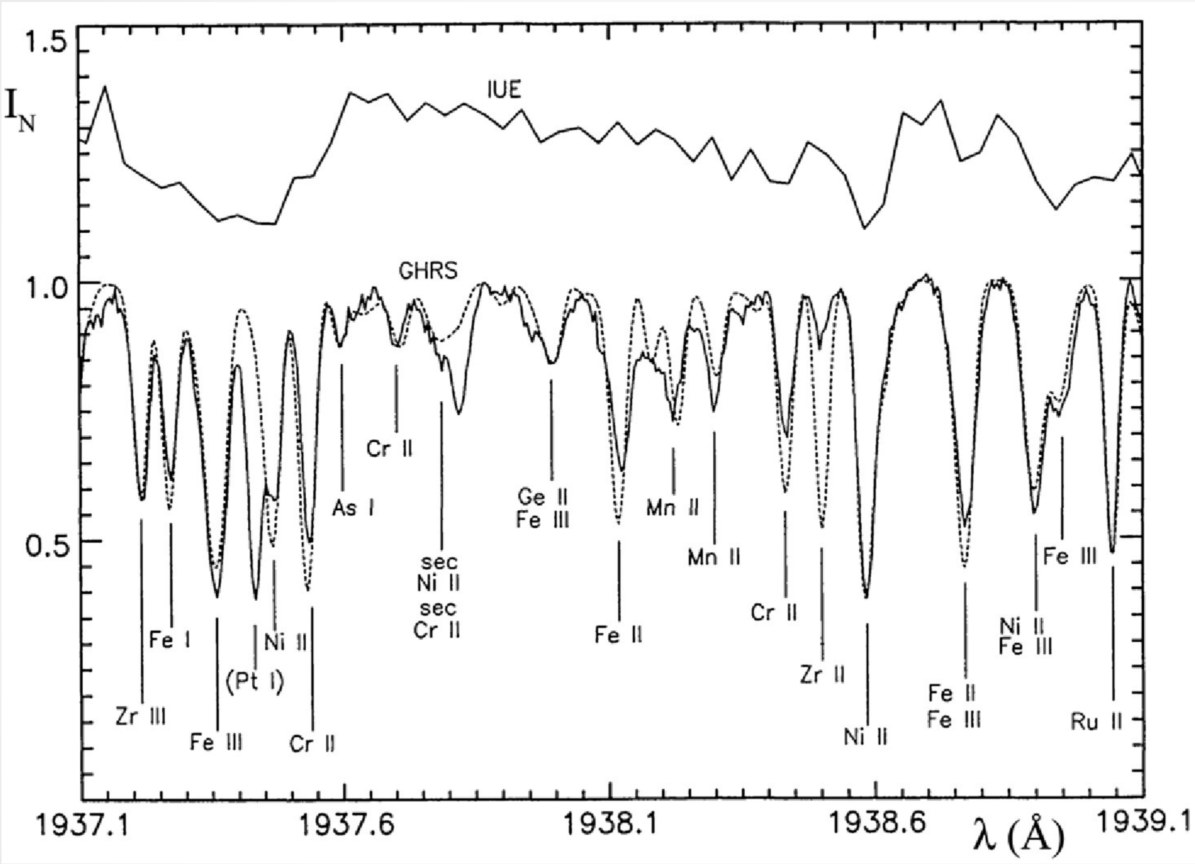
Opis kvantitativno parametrima:

Komponente
Koncentracija
Srednje rastojanje
Temperatura
Toplotna provodnost
Viskoznost
Jačina struje
Napon pražnjenja
El. provodnost
Ef. presek
Dimenzije



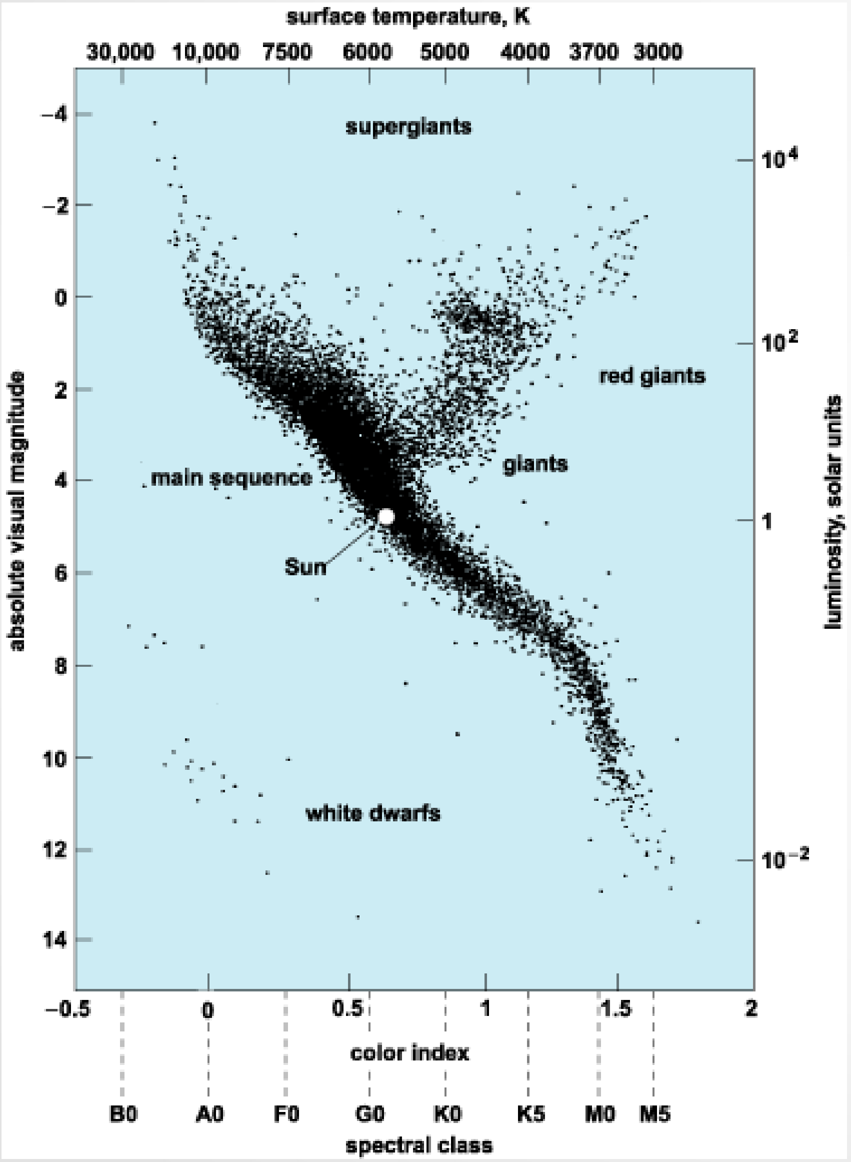
1 eV corresponds to 11606 K

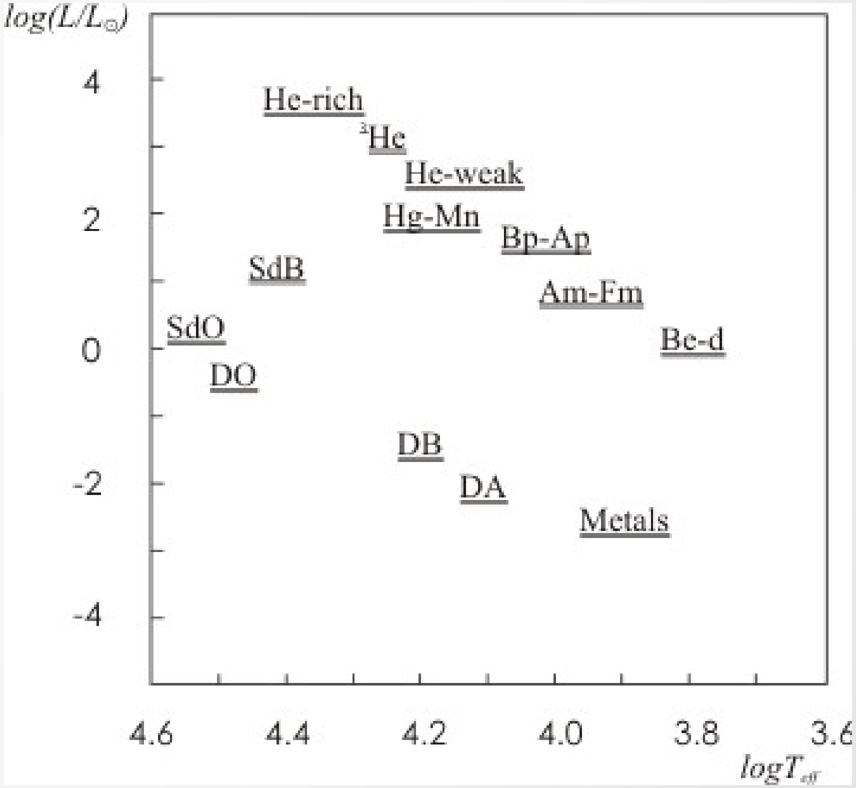
Goddard High Resolution Spectrograph-HST



Ultravioletni spektar zvezde χ Lupi dobijen sa GHRS i sa IUE satelitom (Leckrone at al, 1993), gde je rezolucija spektra dobijenog pomoću GHRS jednaka 0.0023nm, maksimalni odnos signal šum je 95 (Brandt et al, 1999); puna linija, posmatrani GHRS spektar; isprekidana linija, sintetizovani spektar

Chemically Peculiar Stars & White Dwarfs





Mehanizmi širenja spektralnih linija

Profili linija u zvezdanom spektru – informacije o fizičkom stanju i izobilju hemijskih elemenata

Profil - raspodela inteziteta zračenja oko centralne frekvence, ima konačnu širinu.

U literaturi često se koristi termin poluširina u smislu puna širina na polovini maksimalnog intenziteta, a polovina ove vrednosti se naziva polu-poluširina.

laboratorijska plazma: prirodno, Doplerovo, širenje usled pritiska

zvezdana plazma: turbulencija, rotacija i magnetno polje

Uzimajući mogućnost da je formirana spektralna linija kombinacija nekoliko različitih medjusobno nezavisnih uzroka, procesa; rezultujući profil je moguće odrediti konvolucijom nezavisnih profila.

Prirodno širenje

Klasičan model. Emiteri iz plazme pojedinačno mogu se opisati kao klasičan linearni harmonijski oscilator i kao takvi obrazuju skup udruženih oscilatora koji zajedno stvaraju odgovarajuće polje zračenja. Na svaki pojedinačni oscilator deluje zakočna sila samog polja zračenja koje stvara ovaj skup oscilatora usled čega se vremenom energija ovakvog sistema smanjuje.

Jednačina kretanja oscilatora pobudjenog sudarom u elastičnoj sredini ima oblik (Mihalas, 1978):

$$\ddot{x} = -\nu_0^2 x - \gamma \dot{x}.$$

rešenje

$$x = x_0 e^{\mathrm{i}\nu_0 t} e^{-\gamma t/2}.$$

oscilacije slabe sa vremenom uz konstantu prigušenja datu sa

$$\gamma = 2\mathrm{e}^2 \nu_0^2 / 3\mathrm{mc}^3,$$

Prirodno širenje

Obzirom da na profil linije utiče skup oscilatora različitih frekvencija raspodela inteziteta ima Lorencov oblik

$$I(\omega) = I_0(\gamma/2\pi)[(\nu-\nu_0)^2 + (\gamma/2)^2]^{-1}.$$

otuda profil spektralne linije u slučaju prirodnog širenja ima Lorencov oblik, čija je poluširina

$$\mathrm{w_{kl}} = 2\pi \mathrm{c}\gamma/\nu_0^2 = 4\pi \mathrm{e}^2/3\mathrm{mc}^2,$$

$$\mathrm{w_{kl}} = 1.18\times10^{-4}\,\text{Å}.$$

Ovakva vrednost, ista za sve linije, često je mnogo manja od vrednosti dobijenih posmatranjem u laboratoriji ili iz zvezdanih spektra. U svakom slučaju do širenja spektralne linije dolazi kod svakog sistema u kojem postoji slabljenje oscilatornog procesa, što jeste fundamentalna osobina emitera

Doplerovo širenje

Doplerov efekat je posledica kretanja emitera u odnosu na posmatrača.

Konstituenti zvezdane plazme, emiteri, imaju kako termalno tako i turbulentno kretanje. Ako se emiteri koji zrače, kreću ka ili od posmatrača (gledano u pravcu posmatrača) posledica je pomak talasne dužine zračenja ka plavom ili crvenom delu spektra, odnosno ka većim ili manjim frekvencama zračenja. Brzine emitera koji se kreću možemo predstaviti Maksvelovim tipom raspodele. Intenzitet zračenja emitovanog u intervalu (λ, λ + dλ) opisuje se Gausovom funkcijom oblika (Mihalas, 1978):

$$I(\lambda) = (\lambda_{Dopp}\sqrt{\pi})^{-1}\exp[-(\lambda/\lambda_{Dopp})^2],$$

$$\lambda_{Dopp} \sim (2\mathrm{k}T/M)^{1/2},$$

$$\mathrm{w_{Dopp}}(\mathrm{\mathring{A}}) = 7.16\times10^{-7}\lambda(\mathrm{\mathring{A}})\sqrt{T(K)M(a.j.)^{-1}}.$$

Na visokim temperaturama u laboratoriji Doplerovo širenje postaje sve važniji uzrok širenja zbog čega se mora uzeti u obzir.

Širenje usled pritiska

U klasičnom prilazu perturber je zamišljen kao klasična čestica, koja se kreće po odredjenoj trajektoriji i interaguje sa emiterom (Weisskopf,1932). Vreme sudara je veoma kratko, skoro trenutno, a izmedju dva sudara nema perturbovanja emitera. Potencijal interakcije ima oblik:

$$V_p = \frac{\mathrm{C_p}}{r^p},$$

gde su: Cp konstanta interakcije i r rastojanje izmedju perturbera i emitera koje je funkcija vremena r = r(t). Vrednost koeficijenta p odredjuje potencijal interakcije za pojedine mehanizme širenja.

p = 2 linearni Štarkov efekat

p = 3 rezonantno širenje

p = 4 kvadratični Štarkov efekat

p = 6 Van der Valsovo širenje

Širenje usled pritiska

Poluširina spektralne linije u Vajskopf-ovoj aproksimaciji data je sledećim izrazom:

$$w_{\mathrm{Weiss}}[\mathrm{\AA}] = \lambda^2 \mathrm{c}^{-1} \left(\frac{\mathrm{C_p} \Psi_p}{\eta_0 \bar{v}} \right)^{2/p-1} N \bar{v},$$

gde je λ talasna duina, koeficijent Ψp∈{π, 2π, π/2, 3π/8} odredjen koeficijentom p∈{2, 3, 4, 6}, η_0 kritična vrednost faznog pomeraja, $\bar{v}$ medjusobna relativna brzina emitera i perturbera, a N koncentracija perturbera.

Širenje usled pritiska-linearni Štarkov efekat

odlikuje potencijal interakcije $\sim r^{-2}$ ($p = 2, \Psi_2 = \pi$), a C_2 predstavlja linearnu Štarkovu konstantu interakcije

Javlja se kod vodonika i vodoniku sličnih jona kao i kod jako ekscitiranih nivoa nevodoničnih emitera.

Osim toga dolazi do cepanja spektralnih linija na niz komponenti. Broj ovih komponenti i njihovo medjusobno rastojanje raste sa rednim brojem linije u spektralnoj seriji. Pomeranje spektralne linije je zanemarljivo.

Širenje usled pritiska-rezonantno širenje

odlikuje potencijal interakcije $\sim r^{-3}$ ($p = 3$, $\Psi_3 = 2\pi$), a C_3 predstavlja konstantu rezonantnog širenja, rezonantna poluširina spektralne linije (Breene, 1961):

$$w_{\mathrm{Res}}[\mathrm{\mathring{A}}] = \lambda^2 \pi c^{-1} C_3 \left(\frac{2}{\eta_0} \right) N.$$

Nastaje usled interakcije emitera (atoma) koji zrači i perturbera (atoma) koji je sposoban da primi emitovani foton, ako su zadovoljena dva uslova: prvo, da su emiter i perturber atomi iste vrste i drugo, da je rastojanje izmedju gornjeg i donjeg nivoa prelaza odgovornog za posmatranu liniju isto kao rastojanje izmedju osnovnog i jednog od nivoa u perturberu.

Širenje usled pritiska-kvadratični Štarkov efekat

odlikuje potencijal interakcije $\sim r^{-4}$ ($p = 4$, $\Psi_4 = \pi/2$), a C_4 predstavlja kvadratičnu Xtarkovu konstantu interakcije, pomeranje energetskog nivoa ima kvadratnu zavisnost ($\propto E^2$, gde je E jačina električnog polja), otuda i naziv

Nastaje kod atoma i jona koji nisu slični vodoniku, u električnom polju dolazi do cepanja i pomeranja energetskih nivoa srazmerno kvadratu jačine polja. Do širenja i pomeranja spektralne linije dolazi zbog fluktuacije u vrednosti električnog polja koje stvara perturber, odnosno ansambl perturbera.

Širenje usled pritiska-Van der Valsovo širenje

odlikuje potencijal interakcije $\sim r^{-6}$ ($p = 6$, $\Psi_6 = 3\pi/8$), a C_6 predstavlja Van der Valsovu konstantu interakcije. Prema adijabatskoj teoriji sudara (Lindholm, 1941, 1945; Foley, 1946) usavršen je klasičan prilaz tako da je izveden novi opšti izraz za poluširinu spektralne linije (Breene, 1961), čime je otklonjen nedostatak Vajskopf-ove teorije:

$$w_{LF}[\text{Å}] = 8.5\frac{\lambda^2}{\pi c}C_6{}^{2/5}\bar{v}^{3/5}N.$$

Van der Valsove sile su malog dometa. Energetska razlika inicijalnog i finalnog stanja emitera nije uvek ista jer zavisi od medjusobnog rastojanja emitera (atom, jon ili molekul) i perturbera(neutrala). Posledica ove nejednakosti ogleda se u tome da emitovani fotoni imaju različitu talasnu dužinu. Do proširenja spektralne linije dolazi usrednjavanjem verovatnoća svih mogućih rastojanja izmedju interagujućih čestica, otuda najverovatnijem rastojanju odgovara maksimalan intenzitet linije.

karakterističan za hladnije zvezde spektralnog tipa K,G,M

Štarkovo širenje

Uzrok širenja spektralne linije je promenljivo električno polje koje stvara perturber odnosno ansambl perturbera u prostoru i vremenu. Različitost mogućih interakcija izmedju emitera i perturbera uslovljava raznolikost u doprinosima celokupnom profilu spektralne linije, kako u njenom centru tako i u njenim krilima.

<u>I prilaz: Unificirani metod</u> ispituje profil linije kao celine (Brissaud & Frisch, 1971; Seidel, 1977ab)

<u>II prilaz: podgrana - sudarna aproksimacija</u> (sudarna teorija: Baranger, 1958abc; Griem, Baranger, Kolb & Oertel, 1962; Sahal-Bréchot, 1969ab) kada se dobro opisuje centralni deo linije

<u>II prilaz: podgrana - kvazistatična aproksimacija</u> (kvazistatiqna teorija: Holtsmark, 1919,1924; Griem, 1964) koja daje dobar opis krila linije

Štarkovo širenje

SC-semiklasična teorija (Sahal-Bréchot,1969a)

MSE-modifikovana semiempirijska teorija (Dimitrijević & Konjević, 1980; Dimitrijević & Kršljanin, 1986)

Teorijski proračun Štarkove širine i pomaka spektralne linije je obiman i zahtevan zadatak i onda kada imamo na raspolaganju dovoljan broj atomskih parametara. Modifikovana semiempirijska teorija omogućava jednostavniji proračun Štarkove širine i pomaka spektralnih linija jonizovanih atoma, bez poznavanja velikog broja atomskih parametara.

Štarkovo širenje - SC

U okviru semiklasične teorije (Sahal-Bréchot, 1969ab) emiter (atom koji zrači) opisan je kvantno-mehanički dok su perturberi (elektroni ili joni) predstavljeni kao klasične čestice sa dobro definisanom brzinom kretanja i klasičnim sudarnim parametrom. Izmedju sistema klasičnih perturbera i kvantno-mehaničkog atoma veza je vremenski zavisan potencijal interakcije.

$$\mathrm{w} + \mathrm{id} = N\int_0^{+\infty} v f(v) dv \int_0^{+\infty} 2\pi\rho d\rho (1 - S_{ii}(\rho, v) S_{ff}^{-1}(\rho, v))_{sr},$$

gde N predstavlja koncentraciju elektrona, f(v) funkciju raspodele relativnih brzina v perturbera, ρ klasičan sudarni parametar, S matricu rasejanja, i i f inicijalne i finalne energetske nivoe u atomu (i’ i f’ 0 odgovarajući perturbujući nivoi), a oznaka sr označava ugaono usrednjavanje. Za Maksvelovu raspodelu funkcija ima oblik:

$$f(v) = 4\pi(\frac{\mathrm{m}}{2\pi \mathrm{k}T})^{3/2} v^2 \exp(-\frac{\mathrm{m}v^2}{2\mathrm{k}T}).$$

Štarkovo širenje - SC

Širina i pomak spektralne linije

$$2\mathrm{w} = N\int_0^{+\infty} v f(v) dv \Big(\sum_{i'\neq i} \sigma_{ii'}(v) + \sum_{f'\neq f} \sigma_{ff'}(v) + \sigma_{el}\Big),$$

$$W(\mathring{A}) = \frac{\lambda^2}{2\pi c} W(s^{-1}),$$

$$\sum_{j'\neq j} \sigma_{jj'}(v) = \frac{1}{2}\pi R_1{}^2 + \int_{R_1}^{R_D} 2\pi\rho d\rho \sum_{j'\neq j} P_{jj'}(\rho, v),$$

$$P_{jj'}(\rho, v) = S^2_{jj'}(\rho, v).$$

$$\sigma_{el} = 2\pi R_2{}^2 + \int_{R_2}^{R_D} 8\pi\rho d\rho \sin^2\delta,$$

$$\delta = (\phi_p^2 + \phi_q^2)^{1/2},$$

квадратни корен суме квадрата фазних померају ϕ_p и ϕ_q услед поларизационог потенцијала (r^{-4}) и квадруполног потенцијала (r^{-3}). R_D је Дебајев радијус, а границе R_1, R_2, R_3 описане су у раду Sahal-Bréchot (1969b). Помак линије рачуна се на следећи начин:

$$\mathrm{d} = N\int_0^{+\infty} v f(v) dv \int_{R_3}^{R_D} 2\pi\rho d\rho \sin 2\phi_p.$$

Štarkovo širenje - MSE

U poredjenju sa eksperimentalnim rezultatima, semiempirijski proračuni Štarkovih parametara (Hey, 1976ab; Dimitrijević & Konjević, 1978) za dvaput i triput jonizovane emitere pokazuju sistematski manje vrednosti . Ovaj nedostatak Grimove teorije proizilazi iz činjenice da je Gaunt faktor isti za sve vrste prelaza i sva stanja jonizacije. Osim toga, potreban je isti broj podataka kao i za semiklasičan proračun, a pri tome je tačnost mala. Uzimajući u obzir ove činjenice izveden je novi analitički izraz Štarkovih parametara za širinu i pomak jonskih spektralnih linija (Dimitrijević & Konjević, 1980; Dimitrijević & Kršljanin, 1986).

Štarkovo širenje - MSE

Širina spektralne linije

$$W(\text{Å}) = \frac{\lambda^2}{2\pi c} W(s^{-1}),$$

$$\hbar = h/2\pi$$

$$\mathrm{C} = \frac{8\pi}{3}\frac{\hbar^2}{\mathrm{m}^2}\left(\frac{2\mathrm{m}}{\pi \mathrm{k}}\right)^{1/2}\frac{\pi}{\sqrt{3}},$$

$$\mathrm{w_{mse}} = \mathrm{C}\frac{N}{\sqrt{T}}[\vec{R}^2_{l_i,l_i+1}\tilde{g}(x_{l_i,l_i+1}) + \vec{R}^2_{l_i,l_i-1}\tilde{g}(x_{l_i,l_i-1}) + \\ + \vec{R}^2_{l_f,l_f+1}\tilde{g}(x_{l_f,l_f+1}) + \vec{R}^2_{l_f,l_f-1}\tilde{g}(x_{l_f,l_f-1}) + \\ + \sum_{i'}(\vec{R}^2_{ii'})_{\Delta n\neq 0}g(x_{ii'}) + \sum_{f'}(\vec{R}^2_{ff'})_{\Delta n\neq 0}g(x_{ff'})],$$

$$\tilde{g}(x) = 0.7 - \frac{1.1}{Z} + g(x),$$

$$(E = \tfrac{3}{2}\mathrm{k}T)$$

$$x_{l_k,l_k\pm 1} = \frac{E}{\Delta E_{l_k l_k\pm 1}},$$

$$\vec{R}^2_{l_k,l_k\pm 1} \approx \left(\frac{3n^*_{l_k}}{2Z}\right)^2 \frac{l_{max}}{2l_k+1}[{n^*_{l_k}}^2 - {l_{max}}^2]\Phi^2(n^*_{l-1}, n^*_l, l),$$

$$x_k = \frac{3\mathrm{k}T{n^*_k}^3}{4Z^2\mathrm{E_H}},$$

$$\sum_{k'}(\vec{R}^2_{kk'})_{\Delta n\neq 0} \approx \left(\frac{3n^*_{l_k}}{2Z}\right)^2 \frac{1}{9}\ [{n^*_{l_k}}^2 + 3{l_k}^2 + 3l_k + 11],$$

$${n^*_n}^2 = Z^2[\mathrm{E_H}/(E_j - E_n)],$$

$$g_{kk'} = \frac{\sqrt{3}}{\pi}[\frac{1}{2} + \ln\left(\frac{2Z\mathrm{k}T}{{n^*_k}^2\Delta E_{kk'}}\right)].$$

Štarkovo širenje - MSE

Pomak spektralne linije

$$\mathrm{d_{mse}} = \mathrm{C}\frac{N}{\sqrt{T}}[\vec{R}^2_{l_i,l_i+1}\tilde{g}_{sh}(x_{l_i,l_i+1}) - \vec{R}^2_{l_i,l_i-1}\tilde{g}_{sh}(x_{l_i,l_i-1}) -$$
$$-\vec{R}^2_{l_f,l_f+1}\tilde{g}_{sh}(x_{l_f,l_f+1}) + \vec{R}^2_{l_f,l_f-1}\tilde{g}_{sh}(x_{l_f,l_f-1}) +$$
$$+\sum_{i'}(\vec{R}^2_{ii'})_{\Delta n\neq 0}g_{sh}(x_{n_i,n_i+1}) - 2\sum_{i(\Delta E_{ii'}<0)}[(\vec{R}^2_{ii'})_{\Delta n\neq 0}g_{sh}(x_{i,i'})] -$$
$$-\sum_{f'}(\vec{R}^2_{ff'})_{\Delta n\neq 0}g_{sh}(x_{n_f,n_f+1}) + 2\sum_{f(\Delta E_{ff'}<0)}[(\vec{R}^2_{ff'})_{\Delta n\neq 0}g_{sh}(x_{f,f'})]$$
$$+\sum_k \delta_k],$$

$x \leq 1$

$$\tilde{g}_{sh}(x) = \begin{cases} 0.35, & Z = 2 \\ 0.53, & Z = 3, \\ 0.62, & Z = 4 \end{cases}$$

$$g_{sh}(x) = 0.20.$$

$x \in \{3, 5, 10, 20, 40, 80, 100\}$

$$\tilde{g}_{sh}(x) \in \begin{cases} 0.47, 0.58, 0.70, 0.78, 0.84, 0.86, 0.87, & Z = 2 \\ 0.57, 0.62, 0.70, 0.78, 0.84, 0.86, 0.87, & Z = 3, \\ 0.62, 0.65, 0.70, 0.78, 0.84, 0.86, 0.87, & Z = 4 \end{cases}$$

$$g_{sh}(x) \in \{0.32, 0.45, 0.66, 0.78, 0.84, 0.86, 0.87\}.$$

Štarkovo širenje - MSE

Pomak spektralne linije-uslovi

$Z > 4$

$x < 100 \quad \tilde{g}_{sh}(x) \approx 0.88 - \frac{1.1}{Z} + 0.01\frac{x}{Z},$ $\quad g_{sh}(x) = 0.20.$

$x \geq 100 \quad \tilde{g}_{sh}(x) \approx \frac{\sqrt{3}}{2},$ $\quad g_{sh}(x) \in \{0.32, 0.45, 0.66, 0.78, 0.84, 0.86, 0.87\}.$

$\sum_k \delta_k \neq 0$ $\quad |\Delta E_{kk'}| < |\Delta E_{n,n+1}|.$

$\delta_k = \pm \epsilon_k (R^2_{kk'})[g_{sh}(x_{kk'}) \mp g_{sh}(x_{n_k n_k+1})],$

Štarkovo širenje - UMSE

širina i pomak spektralne linije-uprošćena formula

$$\mathrm{w_{umse}} = \mathrm{C}\frac{\lambda^2 N}{\sqrt{T}}(0.9 - \frac{1.1}{Z})\sum_{k=i,f}\left(\frac{3n_{l_k}^*}{2Z}\right)^2 ({n_{l_k}^*}^2 - {l_k}^2 - l_k - 1),$$

$$\mathrm{C} = 2.216\times10^{-20}\mathrm{m^2K^{1/2}},$$

1. са $\Delta n = 0$ сумирањем свих дозвољених прелаза

$$\mathrm{d_{umse1}}[\text{Å}]\approx 1.108\times10^{-20}\mathrm{m^2K^{1/2}}\frac{\lambda^2[\mathrm{m}]N[\mathrm{m^{-3}}]}{\sqrt{T[\mathrm{K}]}}(0.9 - \frac{1.1}{Z})\frac{9}{4Z^2}S_1,$$

$$S_1 = \sum_{k=i,f}\frac{{n_{l_k}^*}^2\epsilon_k}{2l_k+1}({n_{l_k}^*}^2 - 3{l_k}^2 - l_k - 1),$$

2. ако постоје сви нивои са $l_i\pm1$ и $l_f\pm1$ тада:

$$\mathrm{d_{umse2}}[\text{Å}]\approx 1.108\times10^{-20}\mathrm{m^2K^{1/2}}\frac{\lambda^2[\mathrm{m}]N[\mathrm{m^{-3}}]}{\sqrt{T[\mathrm{K}]}}(0.9 - \frac{1.1}{Z})\frac{9}{4Z^2}S_2,$$

$$S_2 = \sum_{k=i,f}\frac{{n_{l_k}^*}^2\epsilon_k}{2l_k+1}[(l_k+1)[{n_{l_k}^*}^2 - (l_k+1)^2] - l_k({n_{l_k}^*}^2 - l_k^2)].$$

Uslovi važenja MSE

1. Za širinu linije w koja bi bila izolovana u centru i pored slabih zabranjenih komponenti u krilima linije treba da važi (Dimitrijević & Sahal-Bréchot, 1984a):

$$\mathrm{w[nm]} \leq 10^{-9} \lambda^2 \mathrm{[nm]} \min |E_k[\mathrm{cm}^{-1}] - E_{k'}[\mathrm{cm}^{-1}]|.$$

2. Minimalno rastojanje $r_{min}^{[1,2]}$ dva perturbujuća elektrona do emitera je malo u poredjenju sa njihovim medjusobnim rastojanjem $\Delta r_{1,2}$, dakle mala je verovatnoća za višestruke sudare (Griem, 1974):

$$r_{\mathrm{min}}^{[1,2]} << \Delta r_{1,2}.$$

3.Proizvod sudarne zapremine (koja je $\sim r_t^3$, gde je r tipično rastojanje emitera i perturbera) i koncentracije perturbera je mnogo manji od jedinice (Sahal-Bréchot, 1969a):

$$r_t^3 N << 1.$$

4. Plazma mora biti idealna (Dimitrijević et al. 1991), drugim rečima broj perturbera u Debajevoj sferi mora biti mnogo veći od jedinice:

$$N[\mathrm{m}^{-3}] < 1.9 \times 10^{12} T^3 [\mathrm{K}].$$

O primenljivosti podataka o Štarkovom širenju

- za odredjivanje C, N i O obilnosti u zvezdama ranih spektralnih klasa B (Gies & Lambert, 1992)

- za odredjivanje izobilja Mg, Al i Si u zvezdama normalnog kasnog B tipa i Hg-Mg zvezdama (Smith, 1993)

- za odredjivanje izobilja elemenata u toplim patuljcima (Chayer et al. 1995ab)

- za ispitivanja anomalnog izobilja u zvezdama (Michaud & Richer, 1992)

- za analize izobilja elemenata sa DAO spektrogramima za 15 Vulpeculae i 32 Aquarii (Bolcal et al. 1992)

- za računanje ubrzanja zračenja u zvezdanim omotačima (Alecian et al. 1993; Gonzales et al. 1995ab; LeBlanc & Michaud, 1995; Seaton, 1997)

- za ramatranje radijativne levitacije u toplim belim patuljcima (Chayer et al.1995ab; Charo et al. 1999)

- za kvantitativnu spektroskopiju toplih zvezda (Kudritzki & Hummer, 1990) za ne-LTE proračun jačina linija Si u zvezdama spektralnih klasa B (Lennon et al. 1986)

- za proračun i proučavanje zvezdane neprozračnosti (Iglesias et al. 1990; Iglesias & Rogers, 1992; Rogers & Iglesias, 1992, 1995, 1999; Seaton, 1993; Mostovych et al. 1995)

- za ispitivanje zvezdanih atmosfera i vetrova toplih zvezda (Butler, 1995)

- za istraživanje Ga II spektralnih linija u spektrima Ap zvezda (Lanz et al. 1993), itd (videti Dimitrijević, 2003a).

A&A 441, 391–393 (2005)
DOI: 10.1051/0004-6361:20052701

Astronomy & Astrophysics

Stark broadening of Cd I spectral lines*

Z. Simić[1,2], M. S. Dimitrijević[1,2], N. Milovanović[1,2], and S. Sahal-Bréchot[3]

[1] Astronomical Observatory, Volgina 7, 11160 Belgrade, Serbia and Montenegro
e-mail: [zsimic;mdimitrijevic]@aob.bg.ac.yu
[2] Institute Isaac Newton of Chile Yugoslavia Branch, and Universidad Diego Portales, Chile
[3] Observatoire de Paris-Meudon, 92195 Meudon, France

Received 14 January 2005 / Accepted 7 March 2005

Abstract. Stark broadening parameters, widths, and shifts for 33 Cd I singlets and 37 triplets were calculated using the semi-classical perturbation method. The results were compared with available experimental and theoretical data. Also, regularity in the spectral series $5s^2\ ^1S$–$np\ ^1P^\circ$ was investigated. The influence of Stark broadening was analyzed in A-type stellar atmospheres.

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

1. Introduction

Cadmium lines are interesting due to their presence in stellar atmospheres. They have been identified in A-type star spectra, as e.g. 68 Tauri (Adelman 1994a,b), χ Lupi (Leckrone et al. 1999), V816 Centauri (Cowley et al. 2000). As an example Adelman has shown for 68 Tau that the [Cd/H] value (-6.57 ± 0.15) is very large in comparison to the one for the Sun (-10.14). It is worth noting that for the atmosphere modelisation of this star with $T_{\rm eff} = 9025$ K and $\log g = 3.95$ (Adelman 1994a,b), Stark broadening data for C II, Mg II, Si II, and Ca II lines (Sahal-Bréchot 1969a,b; Chapelle & Sahal-Bréchot 1970; Lanz et al. 1988) have been used, which shows the usefulness of such data for A-type star spectra analysis.

The particularity of neutral cadmium is that the line 6438.4696 Å, $5p\ ^1P^\circ_1$–$5d\ ^1D_2$ is the fundamental wavelength on which other standards are based. Moreover, neutral cadmium is important in analytical spectrochemistry because of its significance in toxicological and environmental studies.

The first experimental investigations of the influence of the Stark broadening mechanism on cadmium lines were performed by Nagibina (1958) and by Gorodnichyute & Gorodnichyus (1961). Here, the experimental results obtained by Kusch & Oberschelp (1967) are of interest. Also, the first theoretical determination was by Grechikhin (1969), and in our case we will use the results obtained by Dimitrijević & Konjević (1983) for comparison.

Stark broadening of cadmium lines is also useful when considering of regularities and systematic trends, and the corresponding results may be of interest in astrophysics for interpolation of new data and critical evaluation of existing ones. We note here that the first investigation of regularity in spectral series was that of Wiese & Konjević (1982).

Here, we use the semiclassical perturbation approach (Sahal-Bréchot 1969a,b) to calculate the Stark broadening parameters of 33 Cd I singlets and 37 triplets as a function of electron density for temperatures between 2500 K and 50 000 K, which are particularly interesting for stellar investigation. The results obtained are then used for analysing of the influence of Stark broadening in A-type stellar atmospheres.

2. Results and discussion

For neutral cadmium lines Stark broadening parameters (the full line width at half maximum – W and the line shift – d) were calculated by using the semiclassical perturbation formalism (Sahal-Bréchot 1969a,b). This formalism, as well as the corresponding computer code, 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). A brief review of the calculation procedure, with discussion of updatings and validity criteria is given by Dimitrijević (1996). The atomic energy levels needed for the calculations were taken from Moore (1971). The oscillator strengths were 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) was used.

In Tables 1 and 2 (available only in the electronic form at the CDS), electron-, proton-, and He II-impact broadening parameters for 33 Cd I singlets (Table 1) and 37 Cd I triplets (Table 2) for perturber densities from 10^{13} cm^{-3} up to

* Tables 1 and 2 are only 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/441/391

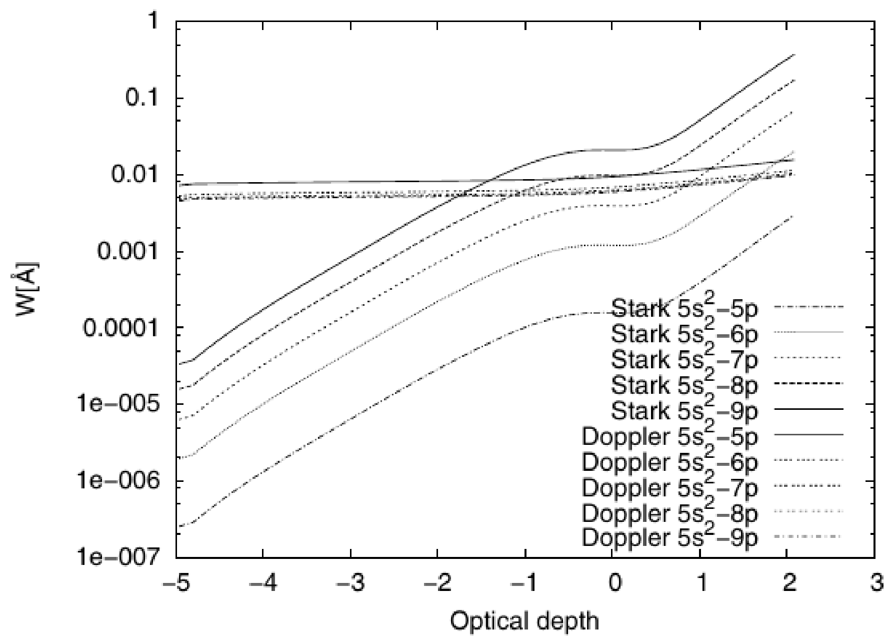


Fig. 2. Thermal Doppler and Stark widths for Cd I singlet spectral lines: $5s^2\ ^1S-5p\ ^1P^\circ$ (2288.7 Å), $5s^2\ ^1S-6p\ ^1P^\circ$ (1669.3 Å), $5s^2\ ^1S-7p\ ^1P^\circ$ (1526.9 Å), $5s^2\ ^1S-8p\ ^1P^\circ$ (1469.4 Å), $5s^2\ ^1S-9p\ ^1P^\circ$ (1440.2 Å) as a function of optical depth.

A&A 469, 681–686 (2007)
DOI: 10.1051/0004-6361:20077054

Astronomy & Astrophysics

The influence of Stark broadening on Cr II spectral line shapes in stellar atmospheres

M. S. Dimitrijević[1,2], T. Ryabchikova[3,4], Z. Simić[1,2], L. Č. Popović[1,2], and M. Dačić[1,2]

[1] Astronomical Observatory, Volgina 7, 11160 Belgrade 74, Serbia
e-mail: mdimitrijevic@aob.bg.ac.yu
[2] Isaac Newton Institute of Chile, Yugoslavia Branch
[3] Institute of Astronomy, Russian Academy of Science, Pyatnitskaya 48, 119017 Moscow, Russia
[4] Institute for Astronomy, University of Vienna, Türkenschanzstrasse 17, 1180 Vienna, Austria

Received 4 January 2007 / Accepted 12 March 2007

ABSTRACT

Aims. We consider the effect of Stark broadening on the shapes of Cr II spectral lines observed in stellar atmospheres of the middle part of the main sequence.
Methods. Stark broadening parameters were calculated by the semiclassical perturbation approach. For stellar spectra synthesis, the improved version SYNTH3 of the code SYNTH for synthetic spectrum calculations was used.
Results. Stark broadening parameters for Cr II spectral lines of seven multiplets belonging to 4s – 4p transitions were calculated. New calculated Stark parameters were applied to the analysis of Cr II line profiles observed in the spectrum of Cr-rich star HD 133792.
Conclusions. We found that Stark broadening mechanism is very important and should be taken into account, especially in the study of Cr abundance stratification.

Key words. stars: chemically peculiar – line: profiles – atomic processes

1. Introduction

Chromium is one of the most peculiar elements in the atmospheres of magnetic, chemically peculiar stars, where a large number of Cr I and Cr II lines in wide range of excitation energies are identified. Ionized chromium spectral lines are third in number and intensity among metals, before Fe II and Ti II in Ae/Be Herbig Star V 380 Ori, where Shevchenko (1994) found 25 Cr II lines. Ionized chromium lines were found for example in α UMi (Polaris) and HR 7308 by Andrievski et al. (1994) and in the spectrum of XX Oph. Meril (1951) found 58 emission Cr II lines, and Babel & Lanz (1992) investigated the influence of stratification on chromium lines in the Ap 53 Cam star spectrum. Consequently, data on the Stark broadening of Cr II lines are obviously of interest when modelling and analyzing stellar spectra.

Transition probabilities of Cr II lines are known with rather good accuracy due to laboratory measurements (Pinnington et al. 1993; Nilsson et al. 2006) and improved theoretical calculations (Raassen & Uylings 1998)[1], but the Stark damping-constants come mainly from theoretical calculations by Kurucz (1993). There is only one experimental result on the Stark broadening of Cr II spectral lines by Rathore et al. (1984). The Stark width and shift of Cr II 3120.36 Å, 3124.94 Å and 3132.05 Å of the multiplet 5 (4s ^{4}D – 4p ^{4}F°) have been measured in a T-tube plasma. The results have been compared with values predicted from established systematic trends and regularities. Using regularities, Lakićević (1983) also made an attempt to determine Stark broadening parameters of the Cr II 2065.65 Å line.

[1] ftp://ftp.wins.uva.nl/pub/orth

Experimental values of the Stark widths turned out to be more than 1 dex higher than the theoretical values by Kurucz. In the recent stratification study of different chemical elements, including Cr in the atmosphere of Ap star HD 133972, Kochukhov et al. (2006) were obliged to change Stark broadening parameters of Cr II 3421.202, 3422.732 Å lines (multiplet 3) using experimental data for multiplet 5 as a template, in order to obtain closer agreement with observations.

In our previous works (Popović et al. 1999, 2001; Dimitrijević et al. 2003, 2005) we have shown that the Stark effect may change the spectral line equivalent widths by 10–45%. Neglecting this mechanism may therefore introduce significant errors into abundance determinations for A-type stars where the Stark broadening is the most important pressure broadening mechanism. Similarly, Lanz et al. (1988) showed that the influence of Stark broadening on the high-excitation Si II multiplets may be critical for the abundance analysis. On the other hand, high-resolution spectra allowed us to study different broadening effects using well-resolved line profiles.

Taking the importance of Stark broadening for different types of spectroscopic studies into account, we calculated Stark widths and shifts for the strongest Cr II multiplets. In Sect. 2 a description of the Stark broadening parameter calculation is given. Section 3 presents the obtained electron-, proton and ionized helium-impact broadening (Stark) parameters and compares them with the existing experimental data (Rathore et al. 1984) and estimates based on regularities and systematic trends from Rathore et al. (1984). In Sect. 4 the obtained Stark broadening data are used for comparison with Cr II lines observed in the spectrum (from the ESO archive) of the Ap star HD 133792

Results. Stark broadening parameters for Cr II spectral lines of seven multiplets belonging to 4s – 4p transitions were calculated. New calculated Stark parameters were applied to the analysis of Cr II line profiles observed in the spectrum of Cr-rich star HD 133792.

Chromium is one of the most peculiar elements in the atmospheres of magnetic, chemically peculiar stars, where a large number of Cr I and Cr II lines in wide range of excitation energies are identified. Ionized chromium spectral lines are third in number and intensity among metals, before Fe II and Ti II in Ae/Be Herbig Star V 380 Ori, where Shevchenko (1994) found 25 Cr II lines. Ionized chromium lines were found for example in α UMi (Polaris) and HR 7308 by Andrievski et al. (1994) and in the spectrum of XX Oph. Meril (1951) found 58 emission Cr II lines, and Babel & Lanz (1992) investigated the influence of stratification on chromium lines in the Ap 53 Cam star spectrum. Consequently, data on the Stark broadening of Cr II lines are obviously of interest when modelling and analyzing stellar spectra.

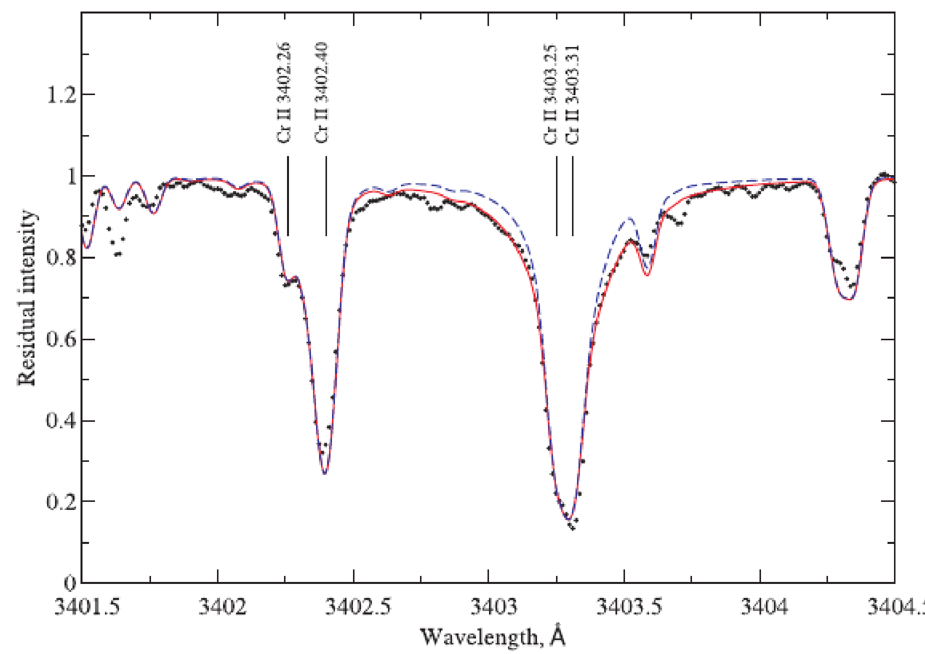


Fig. 4. Comparison between the observed Cr II 3403.30 line profile (dots) and synthetic calculations with the Stark parameters from present paper (full red line) and those from Kurucz (1993) (blue dashed line).

Results. Stark broadening parameters for Cr II spectral lines of seven multiplets belonging to 4s – 4p transitions were calculated. New calculated Stark parameters were applied to the analysis of Cr II line profiles observed in the spectrum of Cr-rich star HD 133792.

Transition probabilities of Cr II lines are known with rather good accuracy due to laboratory measurements (Pinnington et al. 1993; Nilsson et al. 2006) and improved theoretical calculations (Raassen & Uylings 1998)[1], but the Stark damping-constants come mainly from theoretical calculations by Kurucz (1993). There is only one experimental result on the Stark broadening of Cr II spectral lines by Rathore et al. (1984). The Stark width and shift of Cr II 3120.36 Å, 3124.94 Å and 3132.05 Å of the multiplet 5 (4s ^{4}D – 4p ^{4}F°) have been measured in a T-tube plasma. The results have been compared with values predicted from established systematic trends and regularities. Using regularities, Lakićević (1983) also made an attempt to determine Stark broadening parameters of the Cr II 2065.65 Å line.

Experimental values of the Stark widths turned out to be more than 1 dex higher than the theoretical values by Kurucz. In the recent stratification study of different chemical elements, including Cr in the atmosphere of Ap star HD 133972, Kochukhov et al. (2006) were obliged to change Stark broadening parameters of Cr II 3421.202, 3422.732 Å lines (multiplet 3) using experimental data for multiplet 5 as a template, in order to obtain closer agreement with observations.

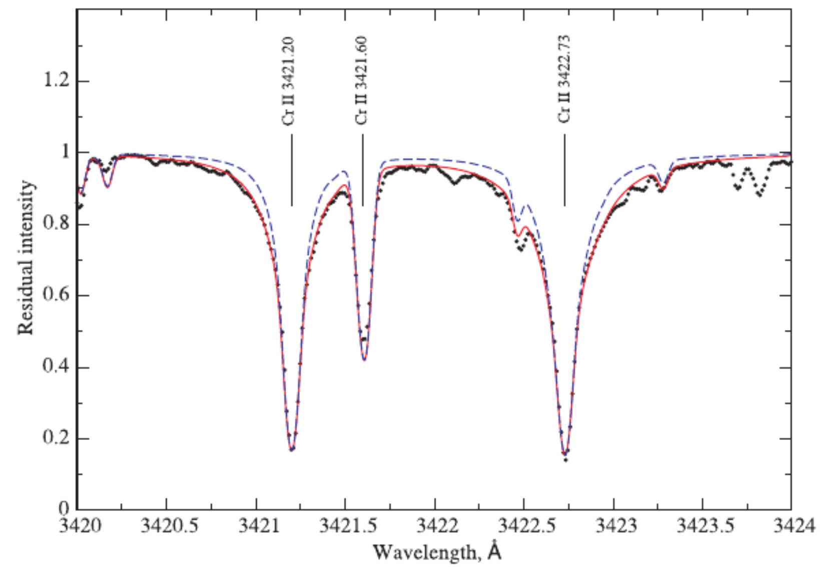


Fig. 6. The same as in Fig. 4 but for the Cr II 3421.20, 3422.73 lines.

Monthly Notices of the ROYAL ASTRONOMICAL SOCIETY
MNRAS **454,** 1736–1741 (2015) doi:10.1093/mnras/stv1970

Stark broadening of Xe VIII spectral lines

Milan S. Dimitrijević,[1,2,3,4★] Zoran Simić,[1★] Andjelka Kovačević,[5] Aleksandar Valjarević[6] and Sylvie Sahal-Bréchot[3★]

[1]*Astronomical Observatory, Volgina 7, 11060 Belgrade, Serbia*
[2]*IHIS – Techno Experts, Bežanijski put 23, 11080 Zemun, Serbia*
[3]*LERMA, Observatoire de Paris, PSL Research University, CNRS, Sorbonne Universities, UPMC Univ. Paris 06, 5 Place Jules Janssen, F-92195 Meudon Cedex, France*
[4]*Institute Isaac Newton of Chile, Yugoslavia Branch, 11060 Belgrade, Serbia*
[5]*Department of Astronomy, Faculty of Mathematics, Studentski Trg 16, 11000 Belgrade, Serbia*
[6]*Department of Geography, Faculty of Natural Sciences and Mathematics, University of Kosovska Mitrovica, Ive Lole Ribara 29, 38220 Kosovska Mitrovica, Serbia*

Accepted 2015 August 21. Received 2015 August 21; in original form 2015 June 24

ABSTRACT

Stark broadening parameters have been calculated for 60 spectral lines of Xe VIII, for broadening by electron, proton, and He III impacts. For calculations, the semiclassical perturbation approach in the impact approximation has been used. The widths and shifts are provided for temperatures from 20 000 K to 500 000 K and for an electron density of 10^{17} cm^{-3}. Obtained results have been used to study the influence of Stark broadening on spectral lines in DO white dwarf atmospheres and it has been found that exist broad layers where this broadening mechanism is dominant in comparison with thermal Doppler broadening.

Key words: atomic data – atomic processes – line: formation.

1 INTRODUCTION

In many astrophysical plasmas Stark broadening of spectral lines is very important or at least non-negligible and should be taken into account (Beauchamp, Wesemael & Bergeron 1997; Popović et al. 2001b; Dimitrijević 2003; Dimitrijević & Sahal-Bréchot 2014). It is also important for laboratory plasmas (Konjević 1999; Torres et al. 2006), inertial fusion plasma investigation, modelling and analysis (Griem 1992), laser produced plasma analysis and diagnostics (Gornushkin et al. 1999; Sorge et al. 2000), and for various technological plasmas and applications, as e.g. for laser welding and piercing (Hoffman, Szymański & Azharonok 2005; Dimitrijević & Sahal-Bréchot 2014), light sources based on plasma, and laser design and developing (Csillag & Dimitrijević 2004; Dimitrijević & Sahal-Bréchot 2014).

In astrophysics, Stark broadening is usually the principal line broadening mechanism for white dwarfs, pre-white dwarf stars, and post-AGB (Asymptotic Giant Branch) stars. Popović, Dimitrijević & Tankosić (1999b), Tankosić, Popović & Dimitrijević (2003), Milovanović et al. (2004), Simić et al. (2006), Dimitrijević et al. (2011), Dufour et al. (2011), Larbi-Terzi et al. (2012), Simić, Dimitrijević & Sahal-Bréchot (2013) and Simić, Dimitrijević & Popović (2014) studied the influence of Stark broadening in DA and DB white dwarf atmospheres and demonstrated its importance. Hamdi et al. (2008) reported the results of a study of the influence of Stark broadening in DO white dwarf atmospheres, on the example of Si VI lines, and shown its dominance in broad region of the atmosphere. Additionally Hamdi et al. (2014) demonstrated on the example of Ar III lines, the importance of Stark broadening in sdB (subdwarf B) star atmospheres.

For temperatures greater or around 10 000 K hydrogen is mainly ionized and Stark broadening is the principal pressure broadening mechanism (Griem 1974), as is the case for A and late B stars, where it must be taken into account for investigation of their atmospheres, which has been analysed for example in Lanz, Dimitrijević & Artru (1988), Popović, Dimitrijević & Ryabchikova (1999a), Popović, Milovanović & Dimitrijević (2001a), Popović et al. (2001b), Dimitrijević et al. (2003a,b), Tankosić et al. (2003), Dimitrijević et al. (2004), Milovanović et al. (2004), Dimitrijević et al. (2005, 2007), Simić et al. (2005a), Simić et al. (2005b) and Simić, Dimitrijević & Kovačević (2009). For example Popović et al. (2001b) demonstrated that, in the case of A-type star atmospheres, the inclusion of Stark broadening can change the equivalent widths by 10–45 per cent, so that abundances, determined neglecting this mechanism, may be with significant errors.

With the development of satellite-born astronomy, earlier astrophysically insignificant data on trace elements become more and more important. So, recently, Werner et al. (2012) reported on the first detection of krypton and xenon in a white dwarf. They analysed spectrum of DO white dwarf RE 0503-289 ($T_{\rm eff}$ = 70 000 K, Dreizler & Werner (1996)), obtained by FUSE (Far Ultraviolet Spectroscopic Explorer) and found 11 Xe VI and Xe VII lines. As shown by Hamdi et al. (2008), Stark broadening is dominant line broadening mechanism in larger part of a DO white dwarf atmosphere.

★ E-mail: mdimitrijevic@aob.rs (MSD); zsimic@aob.rs (ZS) sylvie.sahal-brechot@obspm.fr (SS-B)

Published by Oxford University Press on behalf of the Royal Astronomical Society

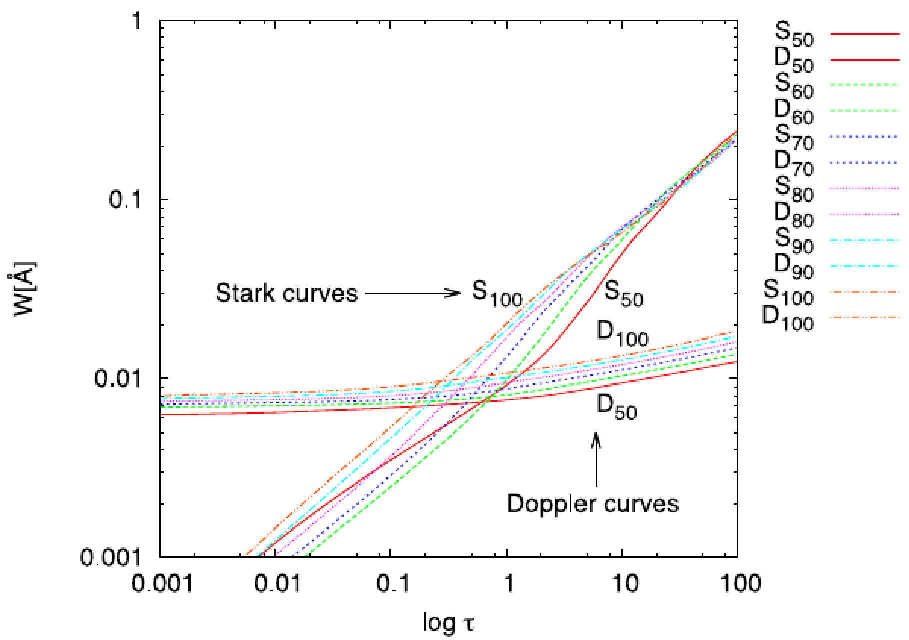


Figure 1. Stark and Doppler widths for Xe VIII 5s $^2S_{1/2}$ – 5p $^2P^o_{1/2}$ ($\lambda = 858.6$ Å) spectral line as a function of logarithm of Rosseland optical depth (log τ). Stark (S) and Doppler (D) widths are shown for six atmospheric models (Wesemael 1981) with effective temperatures from $T_{eff} = 50\,0000$ K (S_{50}, D_{50}) to 100 000 K (S_{100}, D_{100}), and log $g = 9$.

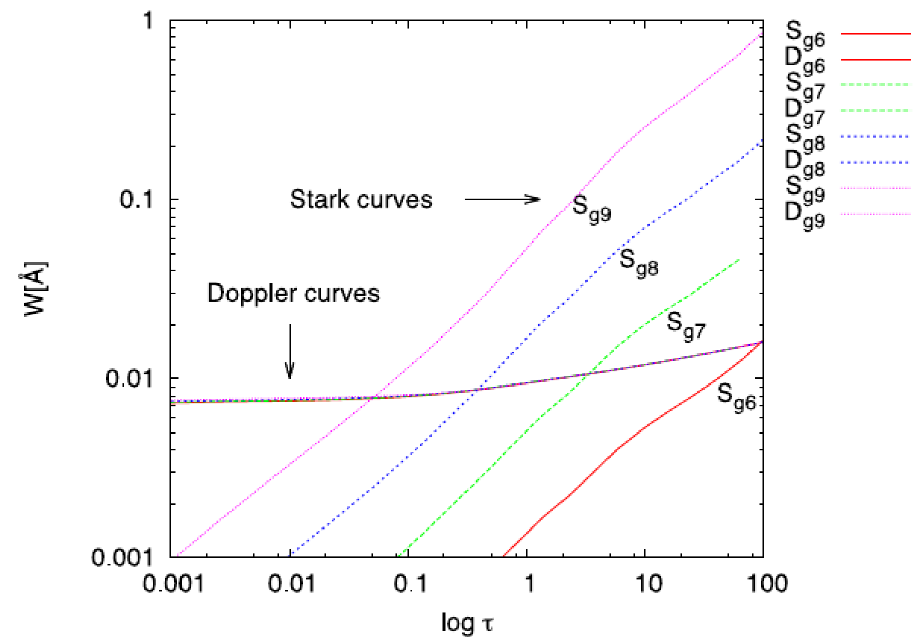


Figure 3. Stark and Doppler widths for Xe VIII 5s $^2S_{1/2}$ – 5p $^2P^o_{1/2}$ ($\lambda = 858.6$ Å) spectral line as a function of logarithm of Rosseland optical depth (log τ). Stark (*S*) and Doppler (*D*) widths are shown for four atmospheric models (Wesemael 1981) with surface gravity from log $g = 6$ (S_{g6}, D_{g6}) to 9 (S_{g9}, D_{g9}), and $T_{eff} = 80\,000$ K. We note that Doppler curves overlap

Available online at www.sciencedirect.com
ScienceDirect
ELSEVIER
New Astronomy 12 (2006) 187–191
New Astronomy
www.elsevier.com/locate/newast

Stark broadening parameters for Cu III, Zn III and Se III lines in laboratory and stellar plasma

Z. Simić *, M.S. Dimitrijević, L.Č. Popović, M.D. Dačić

Astronomical Observatory, Volgina 7, 11160 Belgrade, Serbia and Montenegro

Received 7 June 2006; received in revised form 12 September 2006; accepted 14 September 2006
Available online 4 October 2006
Communicated by G.F. Gilmore

Abstract

Using the modified semiempirical approach, we have considered Stark widths for 6 Cu III, 6 Zn III and 3 Se III transitions where the full semiclassical perturbation approach is not applicable in an adequate way due to the lack of reliable atomic data. Results are obtained as a function of temperature, for perturber density of 10^{17} cm^{-3}. Calculated results have been used to consider the influence of Stark broadening for A type star and DB white dwarf atmospheric conditions.

PACS: 32.70.Jz; 95.30.Ky; 97.10Ex

Keywords: Stark broadening; Line profiles; Atomic data; Stellar atmospheres

1. Introduction

Stark broadening of ion and atom lines is of interest for the investigation of astrophysical plasma, particularly for synthesis and analysis of high resolution spectra obtained from space born instruments. With the development of new techniques, importance of data on trace element spectra like Se or Cu increases. For example, from the analysis of 11 Hg–Mn star spectra (Jacobs and Dworetsky, 1981), where Stark broadening is the main pressure broadening mechanism, it follows that copper is clearly present and overabundant in ten of the investigated stars. Also, the knowledge of Stark broadening parameters is of interest for the investigation of laboratory and technological plasmas.

For example, spectral lines of Cu III and Cu IV are of particular interest for the diagnostic and modelling of plasma created in electromagnetic macro particle accelerators (see Rasheig and Marshall, 1978), where in experimental work, the plasma is usually created by Cu or Al foil evaporation. Stark widths for six Cu IV multiplets of interest for such plasma have been calculated within the modified semiempirical approach (Dimitrijević and Konjević, 1980) in Dimitrijević et al. (1994). One of our aims here is to complete such data with the relevant Stark broadening data for Cu III lines.

Zinc spectral lines are present in stellar spectra (see Adelman, 1994; Cowley et al., 2000; Ryabchikova et al., 2000; Piskunov and Kupka, 2001). Moreover, doubly charged zinc ion is a member of the nickel isoelectronic sequence, known to include possible candidates for development of ultraviolet lasers (Gayasov and Ryabtsev, 1992).

Selenium, a trace element without an astrophysical significance before, is now detected in the atmospheres of cool DO white dwarfs (Chayer et al., 2005a,b).

Here, we present Stark widths for six transitions of Cu III, six transitions of Zn III and three transitions of Se III calculated by using the modified semiempirical approach (see Dimitrijević and Konjević, 1980a; Dimitrijević and Popović, 2001). Calculated results will be used here also to consider the influence of Stark broadening

* Corresponding author. Tel.: +38 111 3089068; fax: +38 111 2419553.
E-mail address: zsimic@aob.bg.ac.yu (Z. Simić).

1384-1076/$ - see front matter
doi:10.1016/j.newast.2006.09.001

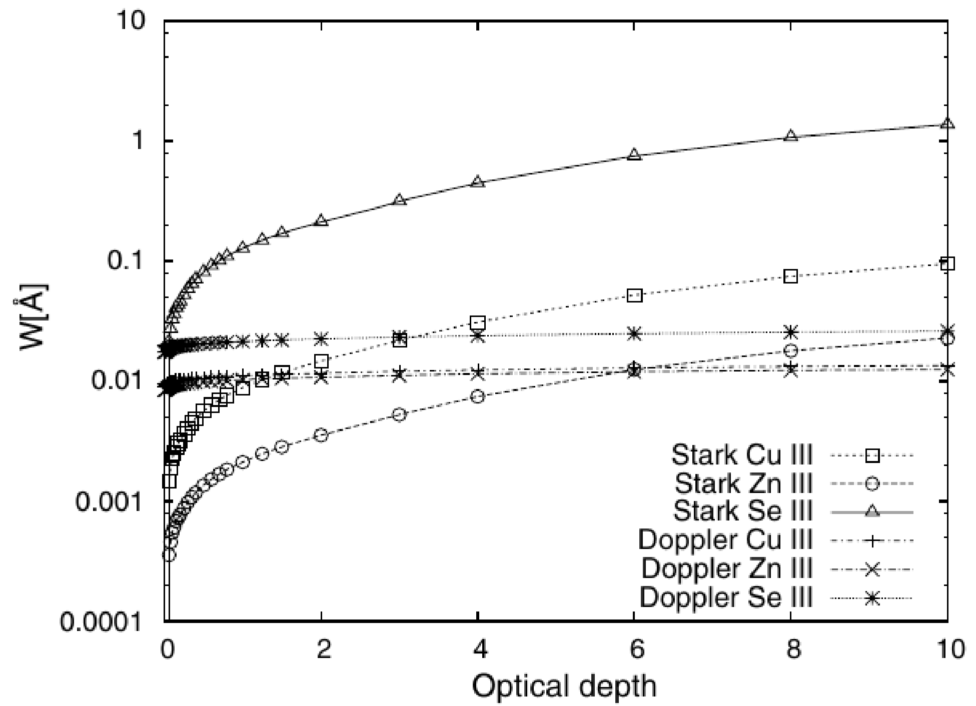


Fig. 2. Thermal Doppler and Stark widths for Cu III, Zn III and Se III spectral lines 4s ^2F–4p $^2G^o$ ($\lambda = 1774.4$ Å), 4s ^3D–4p $^3P^o$ ($\lambda = 1667.9$ Å) and 4p5s $^3P^o$–5p ^3D ($\lambda = 3815.5$ Å) for a DB white dwarf atmosphere model with $T_{\rm eff} = 15{,}000$ K and $\log g = 7$, as a function of optical depth τ_{5150}.

Monthly Notices of the ROYAL ASTRONOMICAL SOCIETY
MNRAS **470,** 1911–1918 (2017) doi:10.1093/mnras/stx1321
Advance Access publication 2017 May 29

Stark broadening of Zr IV spectral lines in the atmospheres of chemically peculiar stars

Zlatko Majlinger,[1★] Zoran Simić[2,4★] and Milan S. Dimitrijević[2,3,4★]
[1]*Faculty of Humanities and Social Sciences, University of Rijeka, 51000 Rijeka, Croatia*
[2]*Astronomical Observatory, Volgina 7, 11060 Belgrade, Serbia*
[3]*LERMA, Observatoire de Paris, F-92195 Meudon Cedex, France*
[4]*Institute Isaac Newton of Chile, Yugoslavia Branch, 11060 Belgrade, Serbia*

Accepted 2017 May 24. Received 2017 May 19

ABSTRACT
Stark widths for 18 Zr IV spectral lines have been calculated by using the modified semi-empirical method. The obtained results have been used to investigate the influence of Stark broadening on the spectra of atmospheres of chemically peculiar stars of A spectral type and hydrogen-rich DA and helium-rich DB white dwarfs. Our results have been used also to test possibility to predict new data using some approximate methods developed on the basis on regularities and systematic trends.

Key words: atomic data – atomic processes – line: formation.

1 INTRODUCTION

Stark broadening parameters of neutral atom and ion lines are of interest for a number of problems in astrophysical, laboratory, laser produced, fusion or technological plasma investigations. Theory and calculation of Stark line broadening in the impact approximation showed a great expansion from the second half of the last century, and are considered now as mature for many applications. Therefore, Stark broadening data could be important for laboratory plasma diagnostics, laser produced plasma investigation and modelling, the design of laser devices, inertial fusion plasma and for analysis and modelling of various plasmas in technology, such as laser welding and piercing and for plasmas in light sources (Hoffman, Szymanski & Azharonok 2006; Shaikh et al. 2016).

As an example, zirconium is a very important metal in the mining industry. The cubic structure of ZrO_2 is a concurrent industrial substitute for a diamond. Recent investigations into the spectrum of zirconium ions in laboratory plasma conditions have already been completed, but without Stark width included (Gaft, Nagli & Gornushkin 2013).

In comparison with laboratory plasmas, conditions in astrophysical plasmas, where the Stark broadening mechanism is important, are incomparably more varied. When Stark broadening is of interest, the corresponding line broadening parameters (line widths and shifts) are significant, for example, for interpretation, synthesis and analysis of stellar spectral lines, determination of chemical abundances of elements from equivalent widths of absorption lines, estimation of the radiative transfer through the stellar atmospheres and subphotospheric layers, opacity calculations, radiative acceleration considerations, nucleosynthesis research and other astrophysical topics.

Zirconium is often found overabundant in HgMn star spectrum. As a member of Sr–Y–Zr triad, zirconium appeared very important in the studying s- and r-processes of nucleosynthesis in HgMn type stars, providing us with useful information about their evolution. The Sr–Y–Zr abundance pattern in chemically peculiar (CP) stars is mostly of two kinds. In the first scenario, Sr is overabundant among the other two elements, which is as a result of the s-process of nucleosynthesis in the deep interior of the star. In the second, Zr or both Zr and Sr, are overabundant, which is a possible consequence of the r-process. However, there is still no strong evidence that abundance of Sr, Y and Zr has some non-nuclear pattern (Allen 1977).

The typical representative member of a non-magnetic subclass of HgMn CP stars is a spectroscopic binary χ Lupi, where Zr is also overabundant, but its spectrum (Leckrone et al. 1993; Sikström et al. 1999) shows very strange behaviour – the zirconium abundance determination from weak Zr II optical and from strong Zr III UV spectral lines gives significantly different results, differing in order of magnitude. This so-called 'zirconium conflict' can probably be justified by not taking into account non-local thermodynamic equilibrium effects or diffusion. However, there can be more solutions – in spite of the binary nature of χ Lupi, zirconium conflict could also be explained by the interaction process between two stellar components. The second component, which is classified as an Ap star, has a longitudinal magnetic field of − 274 G and therefore could represent a possible answer to this question (Mathis & Hubrig 1995). The small radial velocity of the first stellar component can also be a possible reason for the strange behaviour of this HgMn star. Slow rotation that is evident for many HgMn stars could also favour diffusive separation of elements and suppress the meridional circulation (Allen 1977).

★ E-mail: zlatko.majlinger@gmail.com (ZM); zsimic@aob.rs (ZS); mdimitrijevic@aob.rs (MSD)

Published by Oxford University Press on behalf of the Royal Astronomical Society

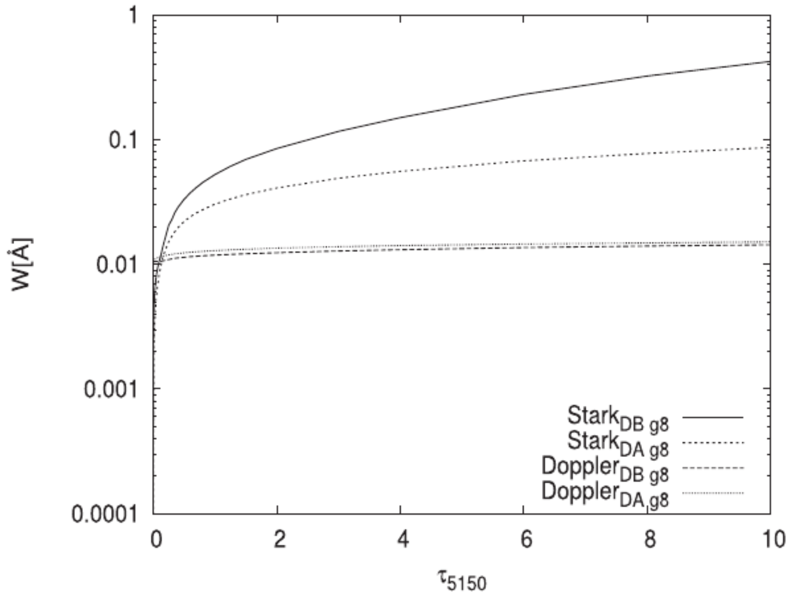


Figure 2. Dependence of electron-impact FWHM and thermal Doppler width on optical depth (τ_{5150}) in the DA and DB White Dwarf atmosphere for Zr IV 5s $^2S_{1/2}$–5p $^2P^o_{1/2}$ $\lambda = 2287.38$ Å spectral line. Models of DA and DB white dwarf atmospheres (Wickramarsinghe 1972) are with parameters $T_{\rm eff}$ =15 000 K and log $g = 8$.

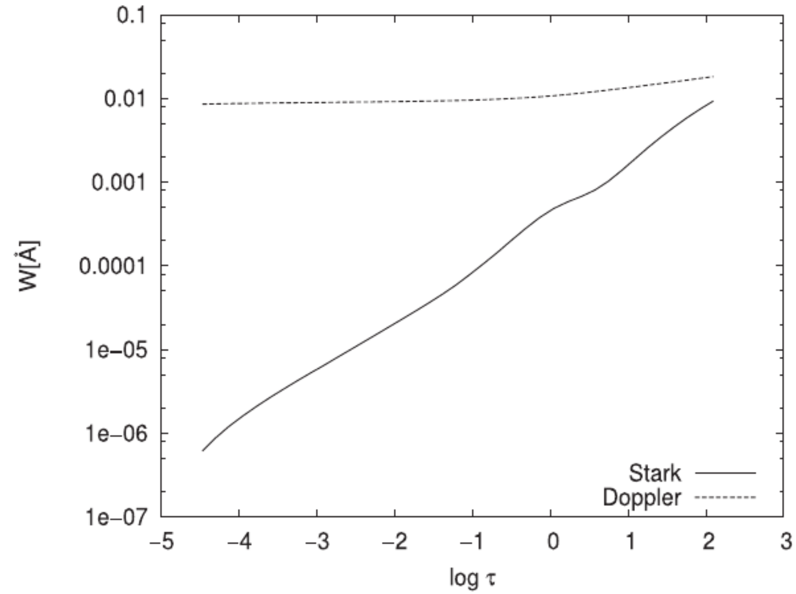


Figure 3. Dependence of Stark (solid) and Doppler (dashed) widths of Zr IV spectral line $\lambda = 2287.38$ Å on optical depth in the atmosphere of an A type star. Model of stellar atmosphere (Kurucz, 1979) is with parameters =10 000 K and log $g = 4.5$.

Monthly Notices of the ROYAL ASTRONOMICAL SOCIETY
MNRAS **491,** 4382–4386 (2020) doi:10.1093/mnras/stz3362
Advance Access publication 2019 December 2

The electron-impact broadening of the Nb III for 5p–5d transitions

Zoran Simić[1]★ and Nenad M. Sakan[2]
[1]*Astronomical Observatory, Volgina 7, 11060 Belgrade, Serbia*
[2]*Institute of Physics, University of Belgrade, PO Box 57, 11001 Belgrade, Serbia*

Accepted 2019 November 27. Received 2019 November 14; in original form 2019 October 24

ABSTRACT

In this work, we present the data of Stark widths of rare-earth element Nb III, calculated for 21 spectral lines by using the modified semi-empirical method. Obtained results have been used to study the influence of Stark broadening on spectral lines in hot stars atmospheres such as A-type star and DA and DB white dwarfs.

Key words: atomic data – atomic processes – line: formation.

1 INTRODUCTION

Abundances analyses show presence of different rare-earth elements (REE) in stellar spectra of hot star atmospheres. The primary astrophysical source of the REE is the rapid neutron-capture process also known as r-process (Mumpower et al. 2016). This mechanism is responsible for the majority of the Solar system REE abundances. Stark broadening data of REE spectral lines are important for abundance determination and also for laboratory and technological plasma.

In the spectrum of Canopus, single ionized niobium is noted by Reynolds, Hearnshaw & Cottrell (1988). Also, Gopka et al. (1991) analyse the abundances of REE elements: strontium, yttrium, zirconium, niobium, molybdenum, ruthenium, rhodium, barium, lanthanum, cerium, praseodymium, neodymium, samarium, europium, and gadolinium in the atmospheres of K giants by the model atmosphere method using synthetic spectra method. From a spectroscopic analysis of the rapidly oscillating chemically peculiar star γ Equ with model of $T_{\rm eff} = 7700$ K, $\log g = 4.20$, Ryabchikova et al. (1997) derived that Nb and Mo are the most overabundant elements in this star relative to the Sun. An example of a very sharp-lined chemically peculiar star, γ Equ, is of spectral class near F0V. This star is a member of the rapidly oscillating CP2 (roAp) stars. It was discovered oscillations with a period of 12.44 min and an amplitude that was variable between 0.5 and 1.5 mmag from night to night.

Identification and quantitative analysis of REE abundance show the spectral lines of the first ions, often the spectral lines of the second and third ions, of REE are dominant in stellar atmospheres due to low ionization potentials (Popović, Dimitrijević & Ryabchikova 1999).

We started to investigate ionized niobium spectral lines in Simić, Dimitrijević & Popović (2014), and we obtained electron-impact (Stark) full width at half-maximum (FWHM) intensity of 15 Nb III spectral lines from 4d^2 (^{3}F)5s–4d^2 (^{3}F)5p transitions. This result shows importance of Stark broadening effect for plasma conditions in atmospheres of A-type stars and DB white dwarfs.

The crucial work on niobium in ionized states II and III is presented in Nilsson et al. (2010). The accurate transition probabilities for astrophysically interesting spectral lines of Nb II and Nb III were derived in order to determine the niobium abundance in the Sun and in metal-poor stars rich in neutron-capture elements. The quality of the presented data lines in laboratory measurements of 17 radiative lifetimes in Nb II. By combining these lifetimes with branching fractions for lines depopulating the levels, Nilsson et al. (2010) derived the transition probabilities of 107 Nb II lines from 4d^{2}5p configuration in the wavelength range 2240–4700 Å, and have presented the theoretical transition probabilities of 76 Nb III transitions with wavelengths in the range 1430–3140 Å.

Complex spectra of REE produce difficulties in calculations for the same approach (Popović & Dimitrijević 1998). Often there are no available data on the energy levels and the reliable transition probabilities for the REE that direct to use the approximate methods suitable for Stark broadening calculations. As we mentioned in Simić et al. (2014), there are many cases where we can use estimate of Stark broadening parameters on the basis of regularities and systematic trends to complete the atomic data needed for calculation (Dimitrijević & Popović 1989).

The spectrum of doubly charged Nb ion is given by Gayazov, Ryabtsev & Churilov (1998), with 908 identified lines in recorded region. The LS coupling is a quite good approximation for niobium in the studied configurations. The analysis of the third niobium spectrum was based on the theoretical level energies and transition probabilities calculated using the COWAN code. The mixing of the terms in the third niobium spectrum configuration is denoted as a mixing configuration term (Gayazov et al. 1998). Details will be given in Section 3 of this paper.

In this work, we presented new electron-impact (Stark) FWHM intensity for 21 Nb III spectral lines and completed a list of obtained results in Simić et al. (2014) within modified semi-empirical approach (MSE; Dimitrijević & Konjević 1980) including the case of complex spectra (Popović & Dimitrijević 1997). This considered

★ E-mail: zsimic@aob.rs

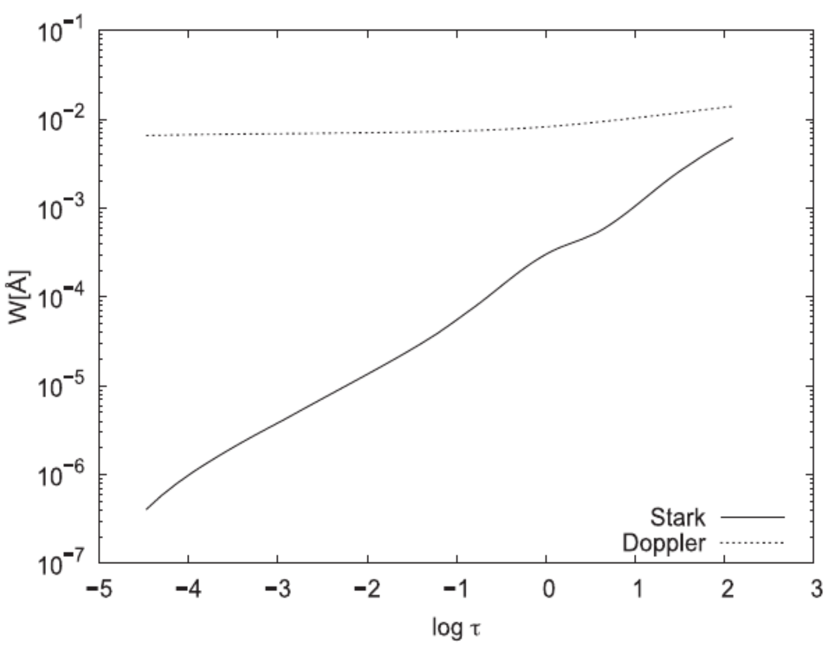


Figure 2. Thermal Doppler and Stark widths for Nb III spectral lines 5p (^{3}F) $^4G_{9/2}$–5d (^{3}F) $^4F^o_{7/2}$ ($\lambda = 1771.5$ Å) for an A-type star atmosphere model with $T_{\rm eff} = 10\,000$ K and $\log g = 4.5$, as a function of the Rosseland optical depth.

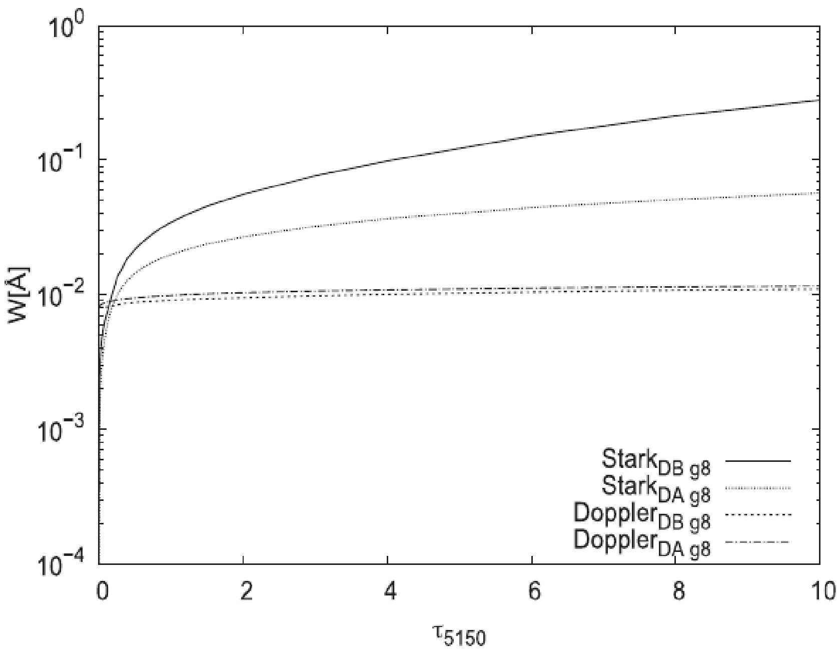
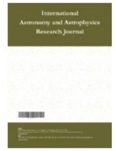


Figure 3. Thermal Doppler and Stark widths for Nb III spectral lines 5p (^{3}F) $^4G_{9/2}$–5d (^{3}F) $^4F^o_{7/2}$ ($\lambda = 1771.5$ Å) for DA and DB white dwarf atmosphere model with $T_{\rm eff} = 15\,000$ K and $\log g = 8$, as a function of optical depth τ_{5150}.



International Astronomy and Astrophysics Research Journal

3(2): 33-47, 2021; Article no.IAARJ.70329

Singly Ionized Iridium Spectral Lines in the Atmosphere of Hot Stars

Zoran Simić[1*], Nenad M. Sakan[2], Nenad Milovanović[1] and Mihailo Martinović[3,4]

[1] *Astronomical Observatory, Volgina 7, 11060 Belgrade, Serbia.*
[2] *University of Belgrade, Institute of Physics, P.O.Box 57, 11001 Belgrade, Serbia.*
[3] *Lunar and Planetary Laboratory, University of Arizona, Tucson, AZ 85721, USA.*
[4] *LESIA, Observatoire de Paris, Meudon, France.*

Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

Article Information

Editor(s):
(1) Prof. Magdy Rabie Soliman Sanad, National Research Institute of Astronomy and Geophysics, Egypt.
(2) Prof. Hadia Hassan Selim, National Research Institute of Astronomy and Geophysics, Egypt.
Reviewers:
(1) Feyisso Sado Bedecha, Addis Ababa University, Jigjiga University, Ethiopia.
(2) Rahul Singh, India.
(3) Ricardo Gobato, Secretariat of State of Parana Education and Sport (SEED/PR), Laboratory of Biophysics and Molecular Modeling Genesis, Brazil.
(4) Gemechu Muleta Kumssa, Ethiopian Space Science and Technology Institute (ESSTI), Ethiopia.
(5) Dmitry Tsipenyuk, Moscow Polytechnic University, Russia.
Complete Peer review History: http://www.sdiarticle4.com/review-history/70329

Received 09 May 2021
Accepted 14 July 2021
Published 19 July 2021

Original Research Article

ABSTRACT

The electron-impact broadening parameters of ion lines are of interest for a number of problems in astrophysical, laboratory, and technological plasma investigations. Singly ionized Iridium lines are confirmed their presence in stellar spectra of the chemically peculiar stars. Our calculations are performed using the modified semiempirical method of Dimitrijević and Konjević. Stark widths for 301 Ir II spectral lines are presented. From the calculated list of lines, the 21 strongest lines from the iridium spectrum are selected with high value of intensity $\geq$ 3000 to demonstrate importance of the Stark broadening mechanism for different types of stars. The analysis of the electron-impact effect on spectral line shapes are performed and obtained Stark and Doppler withds are compared.

Corresponding author: E-mail: zsimic@aob.rs;

We have synthesized the line profiles of 21 Ir II strongest lines using SYNTH code [23] and the ATLAS9 code for stellar atmosphere models [24, 25] in the temperature range of 6000 $\leq T_{eff} \leq$ 16,000 K, and 4.0 $\leq$ log $g \leq$ 5.0. For calculations with SYNTH code we need logarithmic values of Stark widths expressed in $rads^{-1}$ per electron for T = 10,000 K. Also, for the spectrum synthesis parameter A_0 is very useful and can be obtained from corresponding values of log (A_0). In the case of 2152.7 Å we used log A_0=-0.49986 where A_0=4.81915.

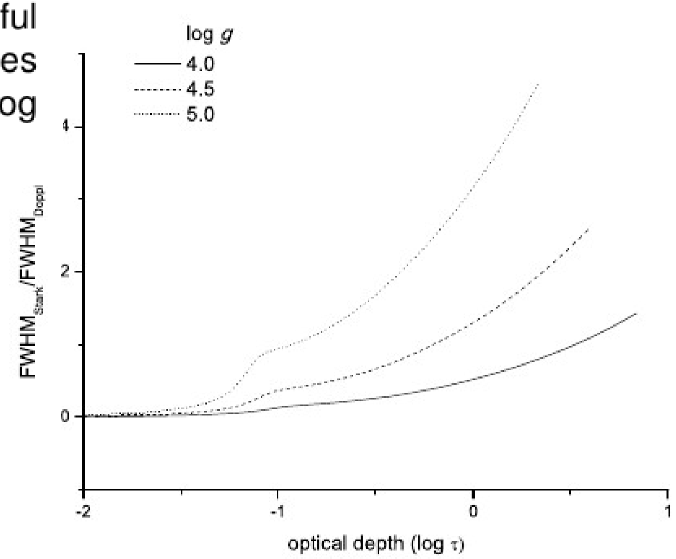


Fig. 3. Width ratio as a function of optical depth, FWHM$_{Stark}$ - Stark width and FWHM$_{Doppler}$ - Doppler width, for the Ir II 2152.7 Å spectral line.

The experimental observation of the spectra of χ Lupi presented in [9] is used in order to check the validity of the theoretically calculated data. The fitting procedure is not related to any synthetic solar spectra model, and presents a best effort fit of the observed spectra to estimate the Stark parameters of Ir II 2282.279. Since the fine structure of the line is not considered, in order to distinguish a Lorentzian and Gaussian component the Voigt profile is used for the fitting of the line. The fitted parameters of the Voigth profile for the Ir II 2282.279 Å line are 0.0134 for the Lorentzian and 0.0368 for the Gauss component of the profile. This result lies in the vicinity of the expected, theoretically calculated values for the Lorentzian component and for the Gausian component of the line, see Fig. 5.

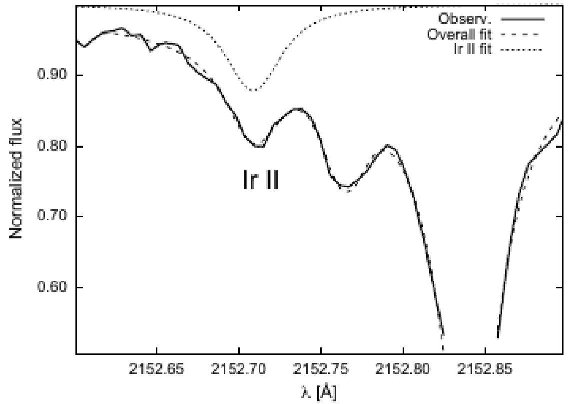


Fig. 5. From the observed spectrum of χ Lupi presented in [9], the fitting procedure is used to extracted the Ir II 2152.7 Å line parameters assuming the Voigt line profile. The solid line presents experimental observation spectra, while the long dashed line is the overall fit, and short dash line is the sought line fit.

HVALA NA PAŽNJI