STARK BROADENING DATA FOR SPECTRAL LINES OF RARE-EATH ELEMENTS: EXAMPLE OF

Tb II,Tb III and Tb IV

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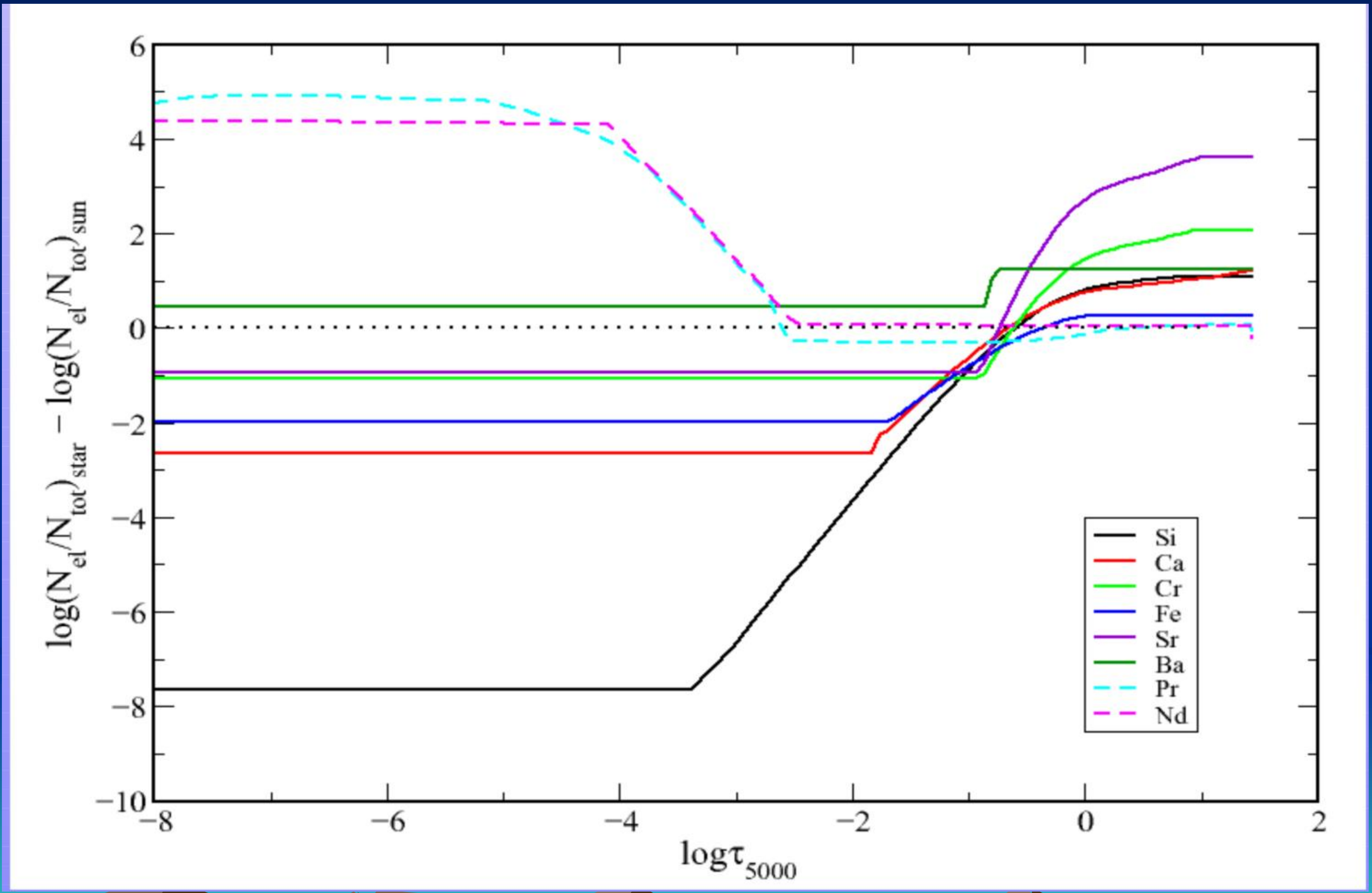
H He
Li Be B C N O F Ne
Na Mg Al Si P S Cl Ar
K Ca Sc Ti V Cr Mn Fe Co Ni Cu Zn Ga Ge As Se Br Kr
Rb Sr Y Zr Nb Mo Tc Ru Rh Pd Ag Cd In Sn Sb Te I Xe
Cs Ba La Hf Ta W Re Os Ir Pt Au Hg Tl Pb Bi Po At Rn
Fr Ra Ac
Ce Pr Nd Pm Sm Eu Gd Tb Dy Ho Er Tm Yb Lu
Th Pa U Np Pu Am Cm Bk Cf Es Fm Md No Lr

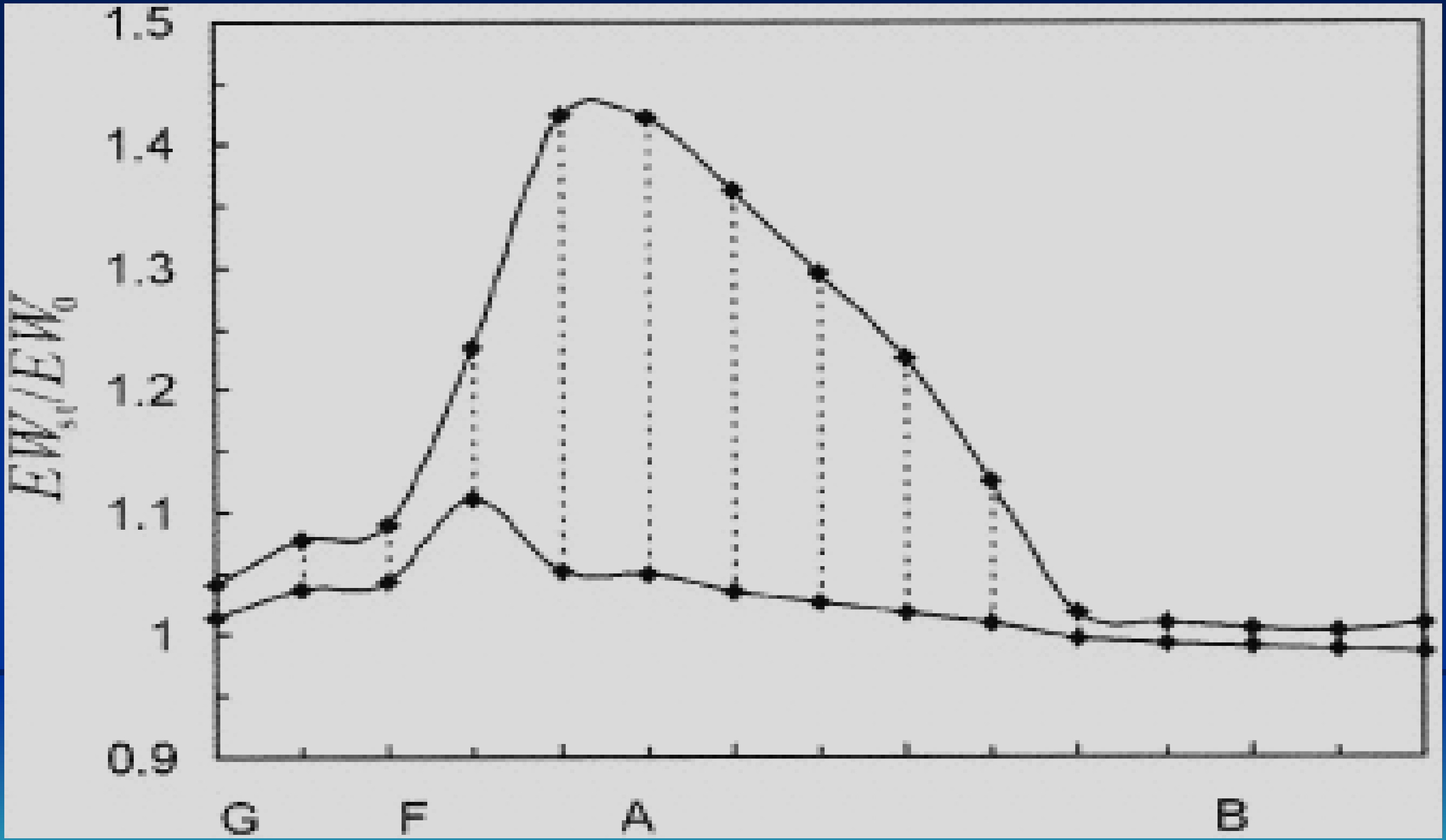
The spectrum of HD 101065 may be the most unusual of all stellar spectra. Its discoverer, the Polish-Australian astronomer, Antoni Przybylski, described the object in a letter to Nature in 1961 as "A G0 Star with High Metal Content."

Tc and Pm identification by Cowley et al (2004) in Przybylski's star and HD 965

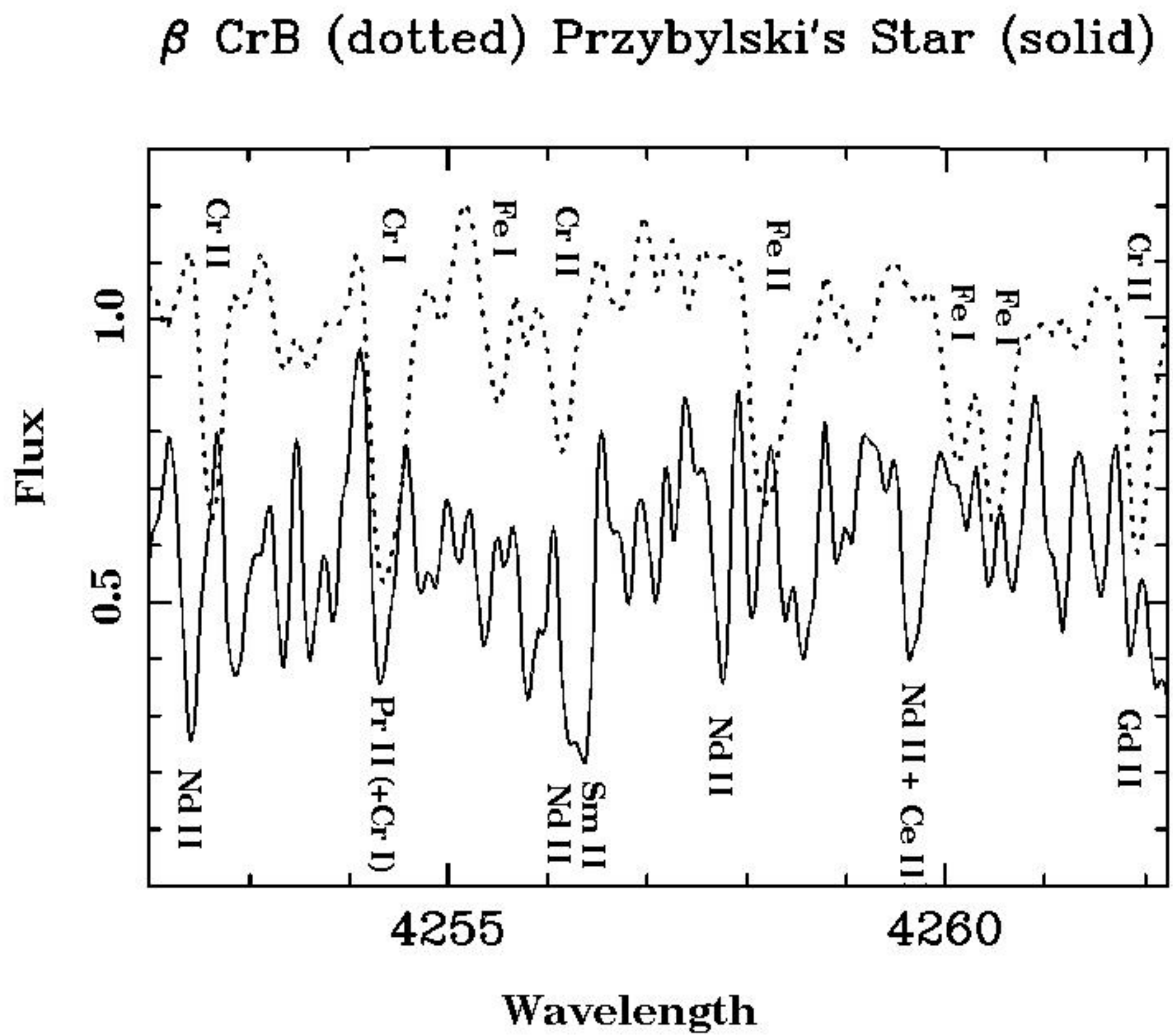
Element distribution in a typical cool Ap star HD 24712 – T. Ryabchikova



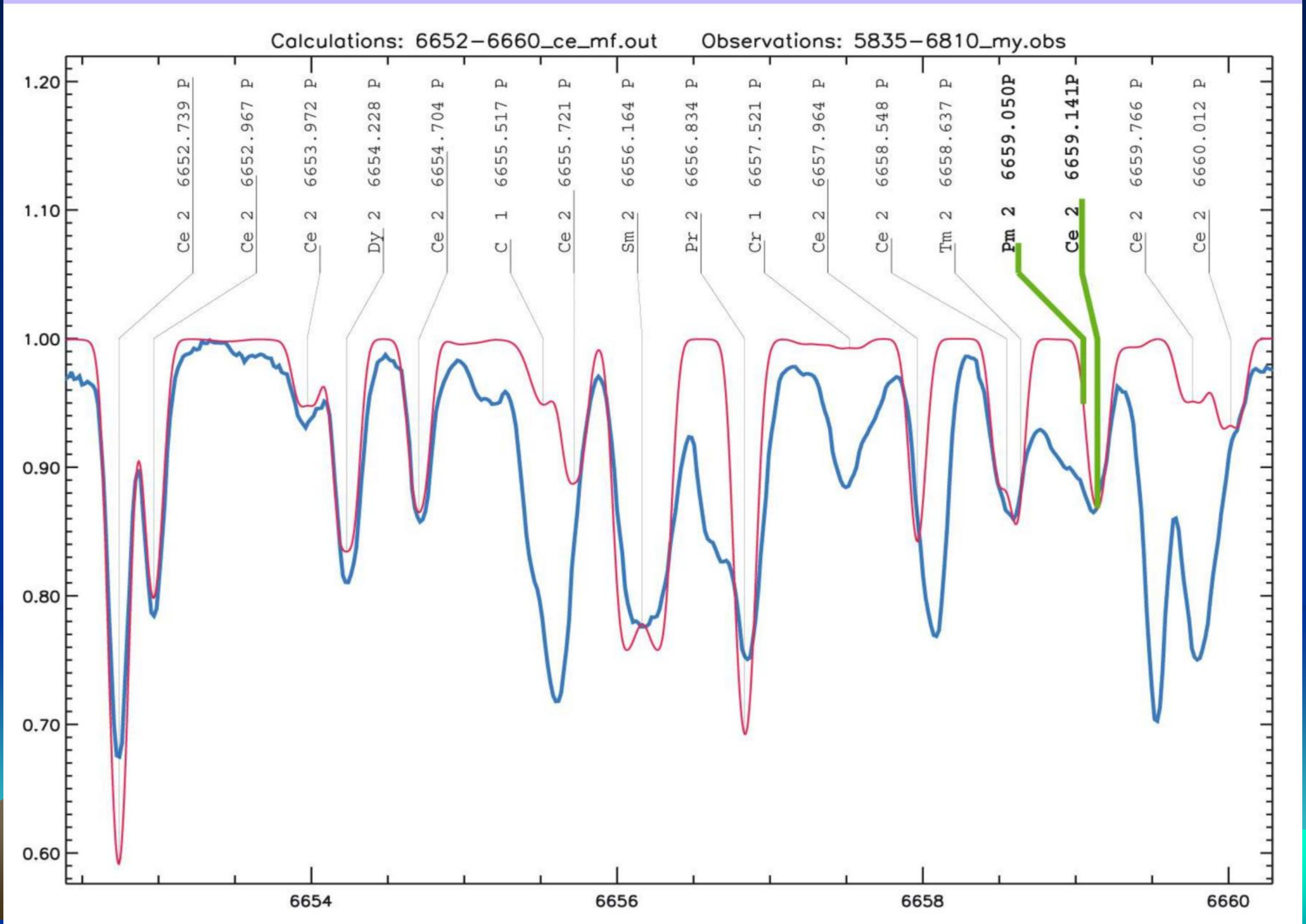
Maximal (upper line) and minimal (lower line) of the ratio of equivalent widths for different stellar types. Maximal and minimal value of EWSt/EW0 are given for 38 considered Nd II lines.



- THE ASTROPHYSICAL JOURNAL SUPPLEMENT SERIES, 135:109-114, 2001
- *STARK BROADENING EFFECT IN STELLAR ATMOSPHERES: Nd II LINES*
- L. C. POPOVIC , S. SIMIC,
- N. MILOVANOVIC, M. S.DIMITRIJEVIC


β CrB (dotted) Przybylski's Star (solid)
Flux
1.0
0.5
Wavelength
4255
4260
Cr II
Cr I
Fe I
Cr II
Fe II
Fe I
Fe I
Cr II
Nd II
Pr II (+Cr I)
Nd II
Sm II
Nd II
Nd II + Ce II
Gd II

T. Ryabchikova

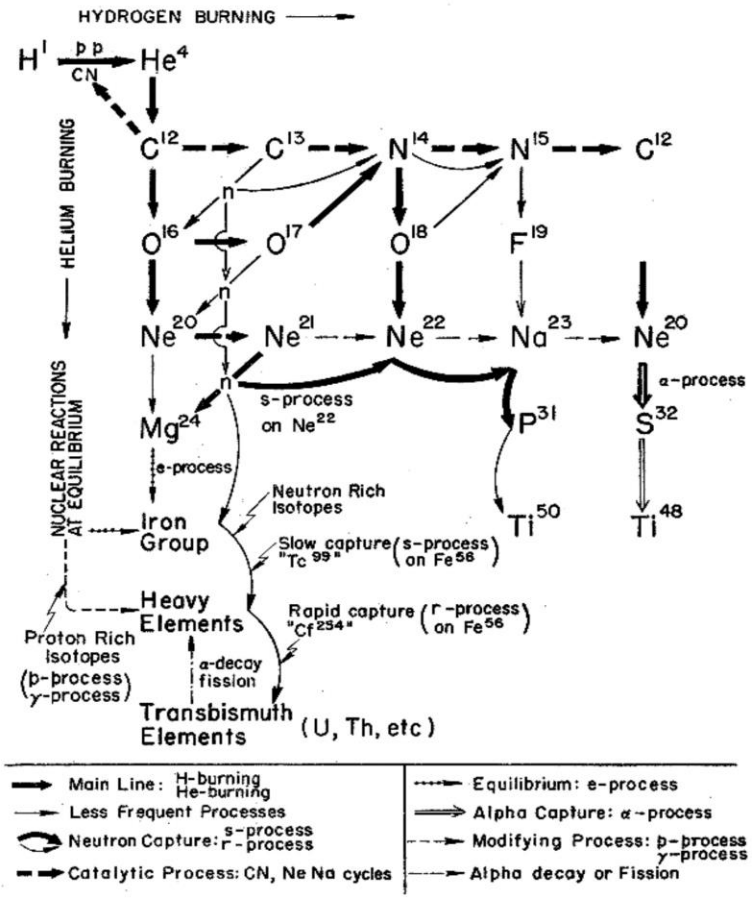


T. Ryabchikova: From 13700 classified Ce II lines in 3000-10000A region about 10000 lines are present in the spectrum of Przybylski's star with intensities higher than 5%.

All known Nd II (1284), Sm II (1327), Gd II (890)are present with intensities more than 20%

Pr III has about 1000 classified lines and 300 are measured in PS

The 1957 milestone



REVIEWS OF
MODERN PHYSICS
ME 29, NUMBER 4 OCTOBER,

Synthesis of the Elements in Stars*

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"It is the stars, The stars above us, govern our conditions";
(*King Lear*, Act IV, Scene 3)

B^2FH – 1957

- **Hydrogen burning**: responsible for most energy production in stars – all cycles synthesizing He from H + isotopes of C,N,O,F,Ne and Na (not produced in He+α)
- **Helium burning**: responsible for synthesis of C from He + production of O^{16}, Ne^{20} and maybe Mg^{24} with extra α-s
- The **α process**: adding α particles to Ne^{20} to form Mg^{24}, Si^{28}, S^{32}, A^{36}, Ca^{40} (and probably Ca^{44} and Ti^{48})
- The ***e* process**: the equilibrium process (very high T and ρ) makes the iron-group (V,Cr,Mn,Fe,Co,Ni)
- The ***s* process**: n-capture with emission of (n,γ) on a long timescale (100yrs-10^5yrs/n-capture); 23<A<46 + good fraction of 63<A<209; abundance peaks at A=90,138,208
- The ***r* process**: n-capture on short timescales (0.01-10s); large fraction 70<A<209 + U,Th + some light isotopes; abundance peaks at A=80,130,194
- The ***p* process**: p-capture with emission of (p,γ) or (γ,n); responsible for p-rich isotopes, with very low abundances

Stellar nucleosynthesis: a recap

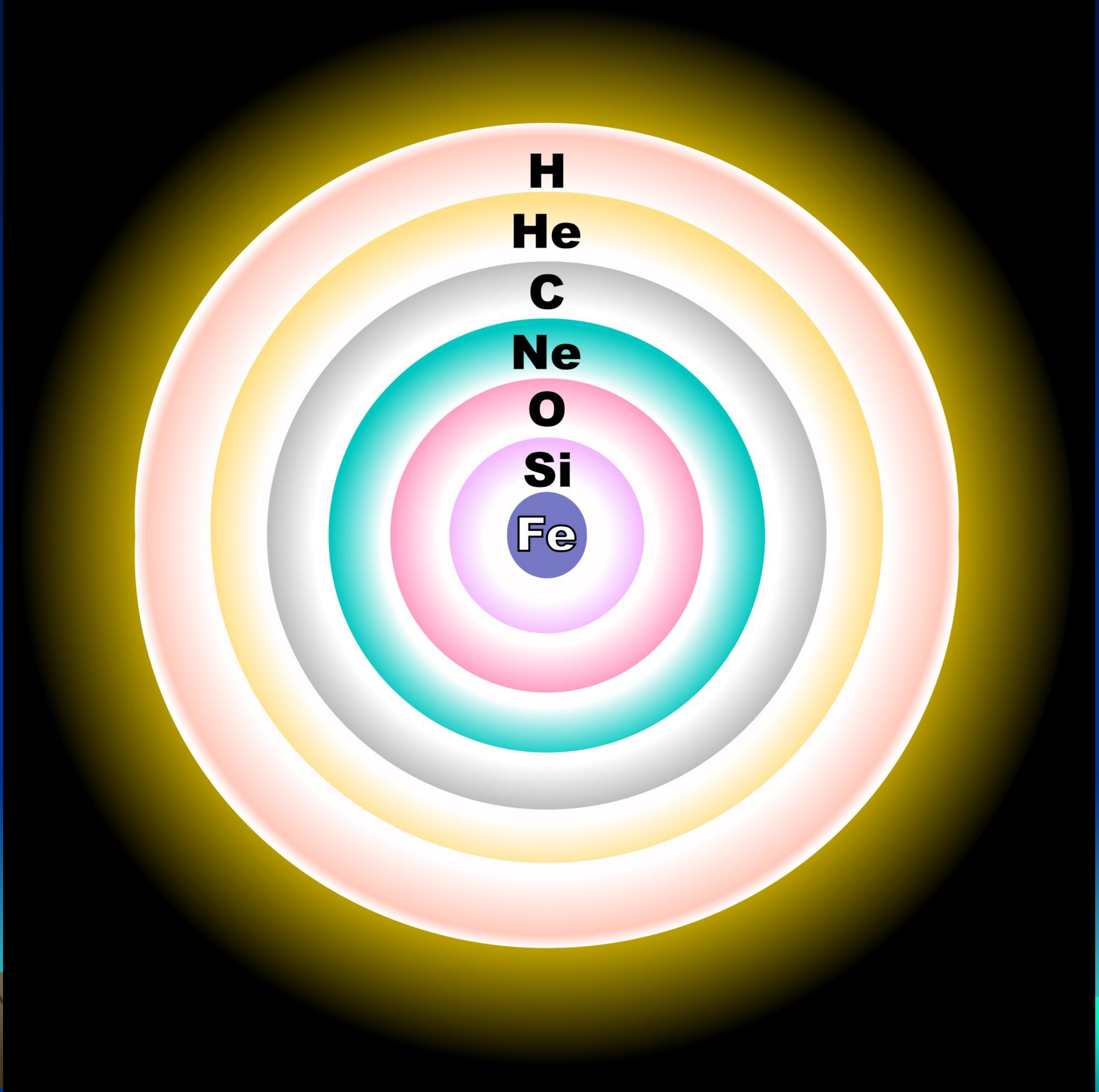
Fuel	Main Product	Secondary Product	T (10^9 K)	Time (yr)	Main Reaction
H	He	^{14}N	0.02	10^7	$4\,H \xrightarrow{CNO} {}^4He$
He	O, C	^{18}O, ^{22}Ne s-process	0.2	10^6	$3\,He^4 \rightarrow {}^{12}C$ $^{12}C(\alpha,\gamma)^{16}O$
C	Ne, Mg	Na	0.8	10^3	$^{12}C + {}^{12}C$
Ne	O, Mg	Al, P	1.5	3	$^{20}Ne(\gamma,\alpha)^{16}O$ $^{20}Ne(\alpha,\gamma)^{24}Mg$
O	Si, S	Cl, Ar, K, Ca	2.0	0.8	$^{16}O + {}^{16}O$
Si, S	Fe	Ti, V, Cr, Mn, Co, Ni	3.5	0.02	$^{28}Si(\gamma,\alpha)$…

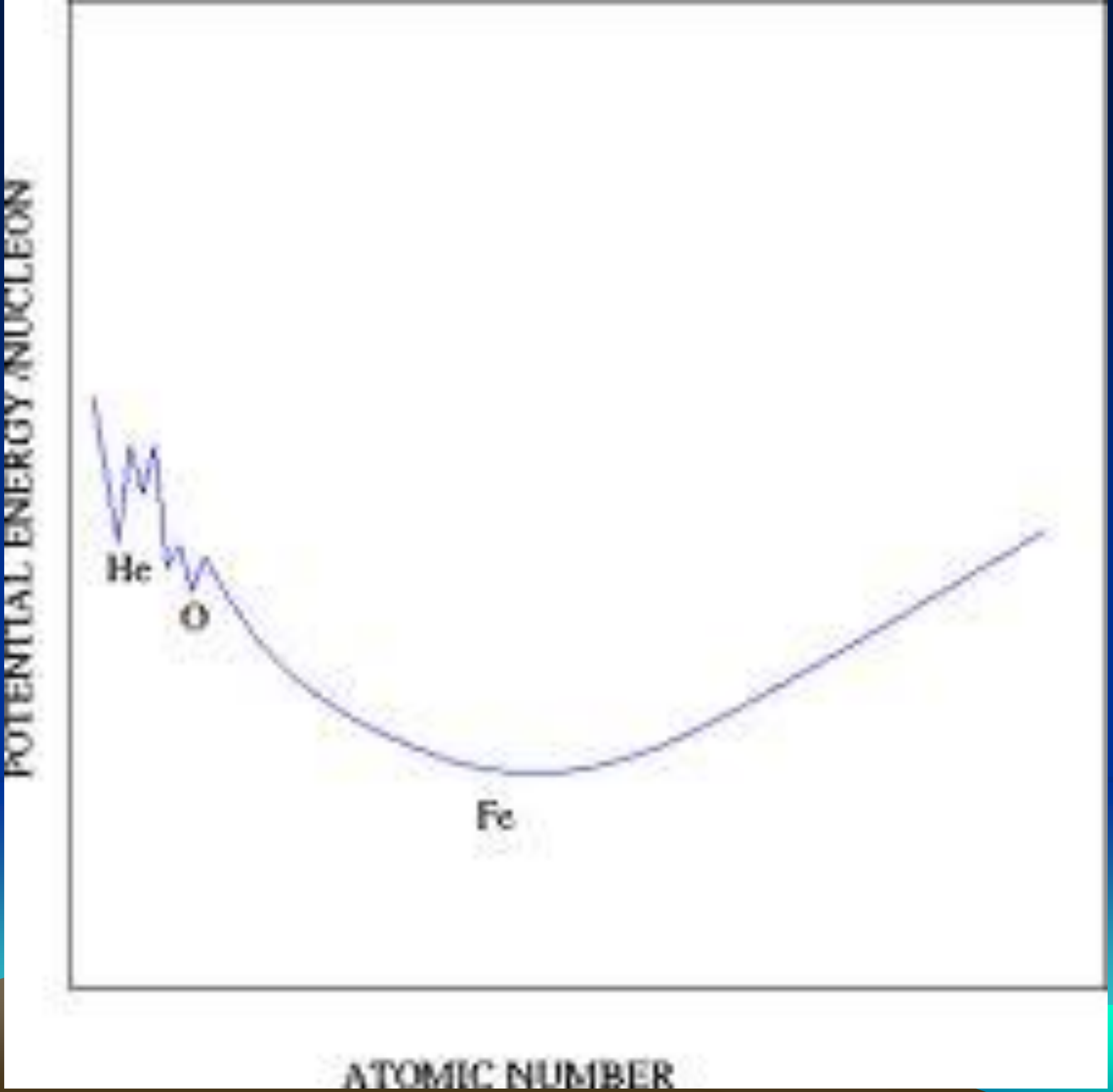
Source: Alex Heger

M/M_{sun}	Fuel	Products	$T/10^8K$
0.08	H	He	0.2
1.0	He	C, O	2 **AGB**
1.4	C	O, Ne, Na	8
5	Ne	O, Mg	15
10	O	Mg … S	20
20	Si	Fe …	30
>8	SNe	All!	

Not all stars undergo the complete sequence → mass!

Only massive stars go straight up to the end.


H
He
C
Ne
O
Si
Fe



POTENTIAL ENERGY /NUCLEON
He
O
Fe
ATOMIC NUMBER

Pm I and Pm III

Primary data source	Query NIST Bibliographic Database for **Pm I**
Martin et al. 1978	Literature on Pm I Energy Levels

Configuration	Term	J	Level (cm^{-1})	Unc ((
$4f^56s^2$	$^6H°$	$^5/_2$	0.00	
		$^7/_2$	803.82	
		$^9/_2$	1 748.78	
		$^{11}/_2$	2 797.10	
		$^{13}/_2$	3 919.03	
		$^{15}/_2$	5 089.79	
$4f^56s^2$	$^6F°$	$^1/_2$	5 249.48	
		$^3/_2$	5 460.50	
		$^5/_2$	5 872.84	
		$^7/_2$	6 562.86	
		$^9/_2$	7 497.99	
		$^{11}/_2$	8 609.21	
		$^7/_2$	17 104.72	
		$^3/_2$	20 006.04	
		$^7/_2$	20 157.85	
		$^5/_2$	20 265.98	

NIST ASD Levels Output

https://physics.nist.gov/cgi-bin/ASD/energy1.pl?encodedlist=XXT2&de=0&spectr

ASD Data Lines Levels Information List of Spectra Ground States & Ionization Energies Bibliography Help

NIST Atomic Spectra Database Levels Data

Pm III 2 Levels Found

Z = 61, Pr isoelectronic sequence

Data on Landé factors and level compositions are not available for this ion in ASD

Primary data source	Query NIST Bibliographic Database for **Pm III** (new window)
	Literature on Pm III Energy Levels

Configuration	Term	J	Level (cm^{-1})	Uncertainty (cm^{-1})	Reference
$4f^55s^25p^6$	$^6H°$	$^5/_2$	0	10	L3974,L3420
Pm IV ($4f^45s^25p^6$ $^5I_4$)	**Limit**	**---**	**[181 000]**	**650**	**L19883c180**

If you did not find the data you need, please inform the ASD Team.

ASD Data Lines Levels Information List of Spectra Ground States & Ionization Energies Bibliography Help

NIST NIST ASD Levels Output

https://physics.nist.gov/cgi-bin/ASD/energy1.pl?encodedlist=XXT2&de=0&spec

NIST Atomic Spectra Database Levels Data

Tb V 2 Levels Found

***Z* = 65, Pm isoelectronic sequence**

Data on Landé factors and level compositions are not available for this ion in ASD

Primary data source		Query NIST Bibliographic Database for **Tb V** (new window)
		Literature on Tb V Energy Levels

Configuration	Term	*J*	Level (cm^{-1})	Uncertainty (cm^{-1})	Reference
$4f^7 5s^2 5p^6$	$^8S°$	$^7/_2$	*0*	*10*	L4095
Tb VI ($4f^7 5s^2 5p^5$)	**Limit**	**---**	**[536 000]**	**2 500**	**L4095**

If you did not find the data you need, please inform the ASD Team.

NIST Atomic Spectra Database Levels Data

Tb VI 2 Levels Found

***Z* = 65, Nd isoelectronic sequence**

Data on Landé factors and level compositions are not available for this ion in ASD

Primary data source		Query NIST Bibliographic Database for **Tb VI** (new window)
		Literature on Tb VI Energy Levels

Configuration	Term	*J*	Level (cm^{-1})	Uncertainty (cm^{-1})	Reference
$4f^7 5s^2 5p^5$			0	10	L582
Tb VII ($4f^8 5s^2 5p^{3°}$)	**Limit**	**---**	**(729 000)**	**36 000**	**L582**

If you did not find the data you need, please inform the ASD Team.

Tb IV 26 Levels Found

Z = 65, Sm isoelectronic sequence

Data on Landé factors are not available for this ion in ASD

Primary data source	Query NIST Bibliographic Database
Martin et al. 1978	Literature on Tb IV Ener

Configuration	Term	J	Level (cm^{-1})
$4f^8$	^{7}F	6	0.0
		5	2 051.6
		4	3 314.2
		3	4 292.3
		2	4 977.9
		1	5 431.8
		0	5 653.8
$4f^7(^8S°)5d$	^{9}D°	2	*51 404.0*
		3	*51 800.8*
		4	*52 399.6*
		5	*53 316.6*
		6	*54 882.5*
$4f^7(^8S°)5d$	^{7}D°	5	*62 680.6*
		4	*63 281.4*
		3	*63 746.2*

		4	*52 399.6*
		5	*53 316.6*
		6	*54 882.5*
$4f^7(^8S°)5d$	^{7}D°	5	*62 680.6*
		4	*63 281.4*
		3	*63 746.2*
		2	*64 081.4*
		1	*64 312.2*
$4f^7(^8S°)6s$	^{9}S°	4	*84 954.5*
$4f^7(^8S°)6s$	^{7}S°	3	*87 573.4*
$4f^7(^8S°_{7/2})6p_{1/2}$	$(^7/_2,^1/_2)$	3	127 839.3
		4	128 636.4
$4f^7(^8S°_{7/2})6p_{3/2}$	$(^7/_2,^3/_2)$	5	134 285.2
		4	135 692.7
		3	136 396.2
		2	136 869.2
Tb V ($4f^75s^25p^6$ $^8S°_{7/2}$)	**Limit**	---	**[317 200]**

If you did not find the data you need, please inform

ASD Data: Lines Levels — Information: List of Spectra, Ground Ionization

J. Quant. Spectrosc. Radiat. Transfer Vol. 24, pp. 451–459
Pergamon Press Ltd., 1980. Printed in Great Britain

STARK WIDTHS OF DOUBLY- AND TRIPLY-IONIZED ATOM LINES†

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(*Received* 28 *March* 1980)

Abstract—In this paper, we report modifications of well known semiempirical and semiclassical approximation formulas for Stark line-width calculations. Comparisons with experiments for doubly ionized atoms yield, as an average ratio of measured to calculated widths 1.06 ± 0.31 for a modified semiempirical formula and 0.96 ± 0.24 for a modified semiclassical formula. For triply ionized atoms these ratios are 0.91 ± 0.42 and 1.08 ± 0.41, respectively. Comparison with other theoretical calculations have also been made.

1. INTRODUCTION

For evaluation of Stark widths and shifts of non-hydrogenic spectral lines of ionized atoms, various theoretical approaches have been used (see, e.g. Ref. 1). Comprehensive calculations of Stark-broadening parameters of spectral lines emitted by singly ionized atoms from lithium through calcium have been performed by Jones *et al.*;[2] the results are included in Ref. 1. These calculations were based on a generalization of semiclassical methods, as used previously for

$$w_{MSE} = N \frac{4\pi}{3c}\frac{\hbar^2}{m^2}\left(\frac{2m}{\pi kT}\right)^{1/2}\frac{\lambda^2}{3^{1/2}} \cdot \left[\sum_{\ell_i \pm 1}\sum_{L_{i'}J_{i'}} \Re^2_{\ell_i,\ell_i\pm 1}\tilde{g}(x_{\ell_i,\ell_i\pm 1}) + \sum_{\ell_f \pm 1}\sum_{L_{f'}J_{f'}} \Re^2_{\ell_f,\ell_f\pm 1}\tilde{g}(x_{\ell_f,\ell_f\pm 1})\right.$$

$$\left. + \left(\sum_{i'} \Re^2_{ii'}\right)_{\Delta n \neq 0} g(x_{n_i,n_i+1}) + \left(\sum_{f'} \Re^2_{ff'}\right)_{\Delta n \neq 0} g(x_{n_f,n_f+1})\right],$$

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

Astron. Astrophys. 172, 345–349 (1987)

ASTRONOMY AND ASTROPHYSICS

Simple estimates for Stark broadening of ion lines in stellar plasmas

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[2] Institute of Physics, YU-11001 Beograd, P.O. Box 57, Yugoslavia

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Summary. Simple analytical expressions for estimation of Stark widths and shifts of ionized atom lines have been derived from the low temperature limit of a modified semiempirical formula.

Key words: lines: profile – atomic and molecular data

1. Introduction

In stellar atmosphere calculations, collisional broadening parameters for a large number of lines of various elements are required

such a situation occurs, considerable simplification of the semi-empirical method occurs (Griem, 1968). The aim of this paper is to obtain in analytical form the low temperature limit of the modified semi-empirical formulae (Dimitrijević and Konjević, 1980; Dimitrijević and Kršljanin, 1986) which can be useful for simple estimates of Stark broadening parameters of singly and multiply charged ion lines in plasmas.

2. Theory

Stark widths and shift of isolated ion lines can be calculated e.g.

$$x_{jj'} = E/|E_{j'} - E_j| \leq 2$$

$$W(\text{Å}) = 2.2151 \times 10^{-8} \frac{\lambda^2(\text{cm}) N(\text{cm}^{-3})}{T^{1/2}(\text{K})} \left(0.9 - \frac{1.1}{Z}\right) \sum_{j=i,f} \left(\frac{3n_j^*}{2Z}\right)^2 (n_j^{*2} - \ell_j^2 - \ell - 1).$$

C. R. Cowley, Observatory, 1971, 139

$$\Gamma_{\mathrm{Stark}} = 5.5 \times 10^{-5} \, \frac{n_{\mathrm{e}}}{\sqrt{T}} \left[\frac{(n_{\mathrm{eff}}^{\mathrm{up}})^2}{z+1} \right]^2,$$

Regularities and systematic trends

Regularities within a given spectrum

-Multiplets nlLJ - n’l’L’J’

-Supermultiplets nlL - n’l’L’

-Transition arrays nl – n’l’

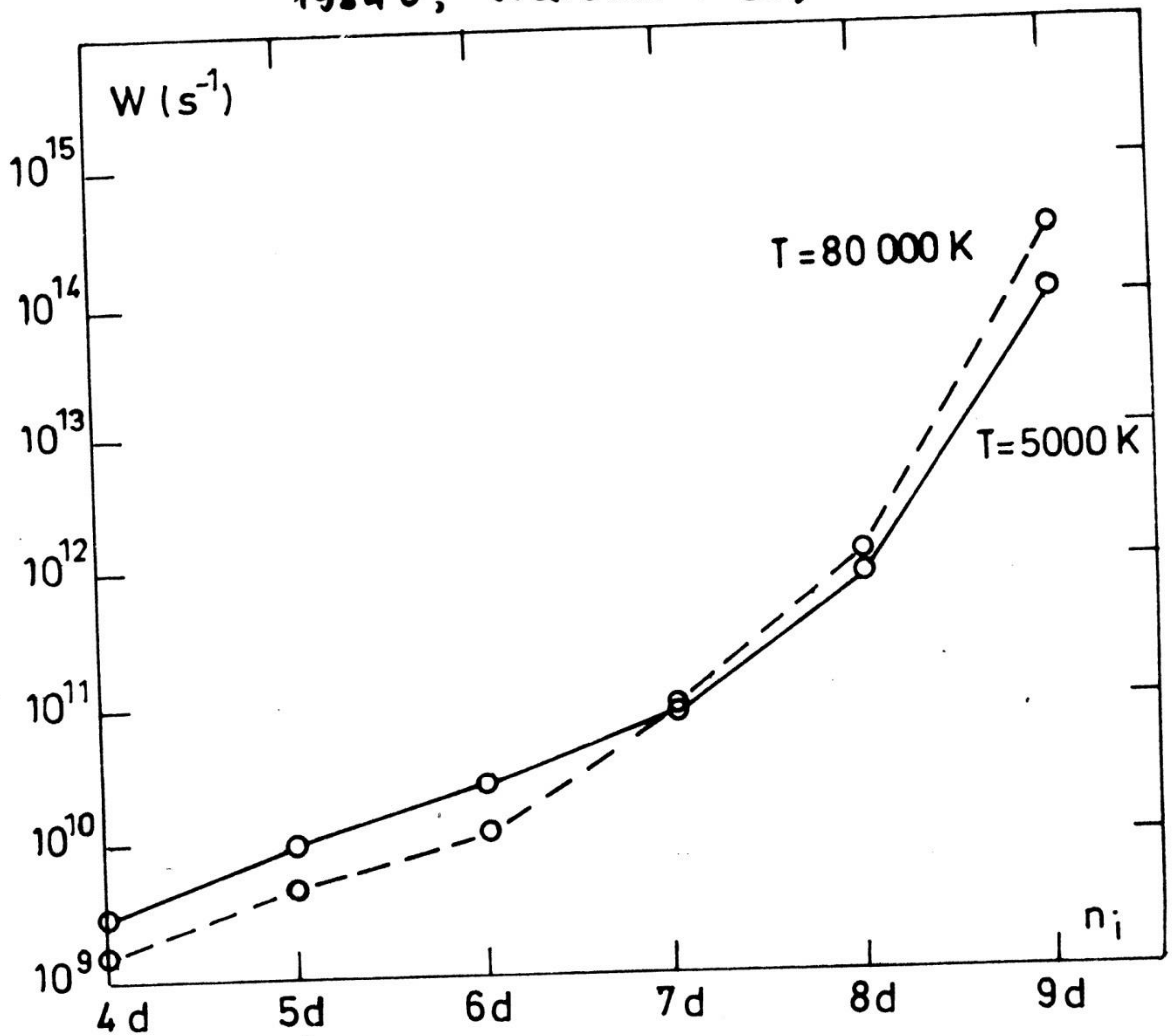
Homologous atoms and ions

Isoelectronic sequences

Other: e.g.: Dependence on the ionization potential

Dependence on polarisability of perturber

DIMITRIJEVIĆ, M.S., & SAHAL-BRÉCHOT, S.:
1984 a, ASTRON. ASTROPHYS. **136**, 289
1984 b, J.Q.S.R.T. **31**, 301



HeI $2p\,^1P^o - nd\,^1D$
ELECTRON IMPACT WIDTH

TRANSITION	T(K)	W(A)	(3kT/2DE)max
Tb II $(^6H^o_{15/2})6s_{1/2}(15/2,1/2)$ - $(^6H^o_{15/2})6p_{1/2}(15/2,1/2)$	5000.	0.393	0.734
3934.1	10000.	0.278	1.47
	20000.	0.196	2.94
$(^6H^o_{15/2})6s_{1/2}(15/2,1/2)$ - $(^6H^o_{15/2})6p_{3/2}(15/2,3/2)$	5000.	0.350	0.556
3610.5	10000.	0.247	1.11
	20000.	0.175	2.22
$(^6H^o_{13/2})6s_{1/2}(13/2,1/2)$ - $(^6H^o_{13/2})6p_{1/2}(13/2,1/2)$	5000.	0.393	0.529
3938.3	10000.	0.278	1.06
	20000.	0.196	2.12
$(^6H^o_{13/2})6s_{1/2}(13/2,1/2)$ - $(^6H^o_{13/2})6p_{3/2}(13/2,3/2)$	5000.	0.344	0.417
3567.3	10000.	0.243	0.834
	20000.	0.172	1.67
	40000.	0.122	3.34
$(^6H^o_{11/2})6s_{1/2}(11/2,1/2)$ - $(^6H^o_{11/2})6p_{1/2}(11/2,1/2)$	5000.	0.397	0.449
3966.1	10000.	0.281	0.897
	20000.	0.198	1.79
	40000.	0.140	3.59

Tb III Stark widths for 88 lines

TRANSITION	T(K)	W(A)	(3kT/2DE)max
Tb III $5d^8G^o$ - $6p_{1/2}$	5000.	0.784E-01	0.215
2369.9	10000.	0.554E-01	0.431
	20000.	0.392E-01	0.861
	40000.	0.277E-01	1.72
	80000.	0.196E-01	3.45
Tb III $5d^8G^o$ - $6p_{3/2}$	5000.	0.707E-01	0.177
2107.6	10000.	0.500E-01	0.354
	20000.	0.354E-01	0.708
	40000.	0.250E-01	1.42
	80000.	0.177E-01	2.83
Tb III $5d^8D^o$ - $6p_{1/2}$	5000.	0.881E-01	0.215
2498.1	10000.	0.623E-01	0.431
	20000.	0.441E-01	0.861
	40000.	0.312E-01	1.72
	80000.	0.220E-01	3.45
Tb III $5d^8D^o$ - $6p_{3/2}$	5000.	0.785E-01	0.177
2208.4	10000.	0.555E-01	0.354
	20000.	0.392E-01	0.708
	40000.	0.277E-01	1.42
	80000.	0.196E-01	2.83

TRANSITION	T(K)	W(A)	(3kT/2DE)max
Tb IV $4f^7(^8S^o)5d\,^9D^o$ - $4f^7(^8S^o_{7/2})6p_{1/2}(7/2,1/2)_3$	5000.	0.275E-01	0.122
1338.7	10000.	0.195E-01	0.243
	20000.	0.138E-01	0.486
	40000.	0.974E-02	0.973
	80000.	0.689E-02	1.95
Tb IV $4f^7(^8S^o)5d\,^9D^o$ - $4f^7(^8S^o_{7/2})6p_{1/2}(7/2,1/2)_4$	5000.	0.273E-01	0.119
1324.5	10000.	0.193E-01	0.239
	20000.	0.136E-01	0.477
	40000.	0.964E-02	0.955
	80000.	0.682E-02	1.91
Tb IV $4f^7(^8S^o)5d\,^9D^o$ - $4f^7(^8S^o_{7/2})6p_{3/2}(7/2,3/2)_5$	5000.	0.255E-01	0.106
1232.3	10000.	0.180E-01	0.211
	20000.	0.128E-01	0.423
	40000.	0.902E-02	0.845
	80000.	0.638E-02	1.69
Tb IV $4f^7(^8S^o)6s\,^9S^o$ - $4f^7(^8S^o_{7/2})6p_{1/2}(7/2,1/2)_3$	5000.	0.161	0.122
2331.8	10000.	0.114	0.243
	20000.	0.807E-01	0.486
	40000.	0.570E-01	0.973
	80000.	0.403E-01	1.95
Tb IV $4f^7(^8S^o)6s\,^9S^o$ - $4f^7(^8S^o_{7/2})6p_{1/2}(7/2,1/2)_4$	5000.	0.156	0.122
2289.3	10000.	0.111	0.243
	20000.	0.782E-01	0.486
	40000.	0.553E-01	0.973
	80000.	0.391E-01	1.95
Tb IV $4f^7(^8S^o)6s\,^9S^o$ - $4f^7(^8S^o_{7/2})6p_{3/2}(7/2,3/2)_5$	5000.	0.128	0.122
2027.1	10000.	0.904E-01	0.243
	20000.	0.639E-01	0.486
	40000.	0.452E-01	0.973
	80000.	0.319E-01	1.95
Tb IV $4f^7(^8S^o)5d\,^7D^o$ - $4f^7(^8S^o_{7/2})6p_{3/2}(7/2,3/2)$	5000.	0.250E-01	0.107
1203.8	10000.	0.177E-01	0.214
	20000.	0.125E-01	0.429
	40000.	0.884E-02	0.858
	80000.	0.625E-02	1.72
Tb IV $4f^7(^8S^o)6s\,^7S^o$ - $4f^7(^8S^o_{7/2})6p_{3/2}(7/2,3/2)$	5000.	0.135	0.107
2056.2	10000.	0.953E-01	0.214
	20000.	0.674E-01	0.429
	40000.	0.477E-01	0.858
	80000.	0.337E-01	1.72

Sc II 6 mult MSE L. Č. Popović and M. S. Dimitrijević, AAS, 120, 373, 1996

Sc III 10 mult. SCP M. S. Dimitrijević and S. Sahal-Bréchot,AAS, 95, 121, 1992

Sc X 4 mult SCP Dimitrijević M.S., Sahal-Bréchot S., AAS, 131, 143, 1998

Sc XI 10 mult,SCP, Ibid

Y II 6 mult, MSE, L. Č. Popović and M. S. Dimitrijević, AAS, 120, 373, 1996

Y III 32 mult. SCP Dimitrijević M. S., Sahal-

Eu II 7 mult. MSE Popović, L.Č., Dimitrijević, M. S.,Ryabchikova, T., AA, 350, 719, 1999

Eu III 1 mult SMSE, Ibid

Nd II 284 lines SMSE L. Č. Popović, S. Simić, N. Milovanović, M. S. Dimitrijević, ApJS, 135, 109, 2001

Yb III 4 lines MSE M. S. Dimitrijević, Atoms **7, 10**, 2019

Tb II 5 mult. SMSE, This conference

Tb III 88 mult. SMSE, This conference

THANK YOU FOR ATTENTION