STARK BROADENING AND WHITE DWARFS

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NEEDS FOR LARGE STARK BROADENING DATA SET

- DEVELOPMENT OF COMPUTERS

  FOR EXAMPLE:

  PHOENIX CODE FOR MODELLING OF STELLAR ATMOSPHERES INCLUDES A PERMANENTLY GROWING DATABASA WITH ATOMIC DATA FOR MORE THAN 500 MILLIONS TRANSITIONS

- SATELLITE BORNE SPECTROSCOPY

STARK BROADENING IS IMPORTANT FOR:

- - ASTROPHYSICAL PLASMAS
- - LABORATORY PLASMAS
- - TECHNOLOGICAL PLASMAS

ASTROPHYSICAL PLASMAS

- Stark broadening may be important for plasma conditions from
- NEUTRON STARS T=10^{+6}-10^{+7}K
- Ne=10^{+22}-10^{+24}cm^{-3}, white dwarfs, hot stars, up to other extreme conditions :
- FOR RADIO RECOMBINATION LINES FROM
- H I (T=50K) AND H II (T=10000K) REGIONS Ne = 1-1000 cm^{-3}

- For example, the influence of Stark broadening within a spectral series
- increases with the increase of the principal quantum number of the upper level and consequently, Stark broadening
- contribution may become significant even in the Solar spectrum.

STARK BROADENING DATA ARE NEEDED IN ASTROPHYSICS FOR EXAMPLE FOR:

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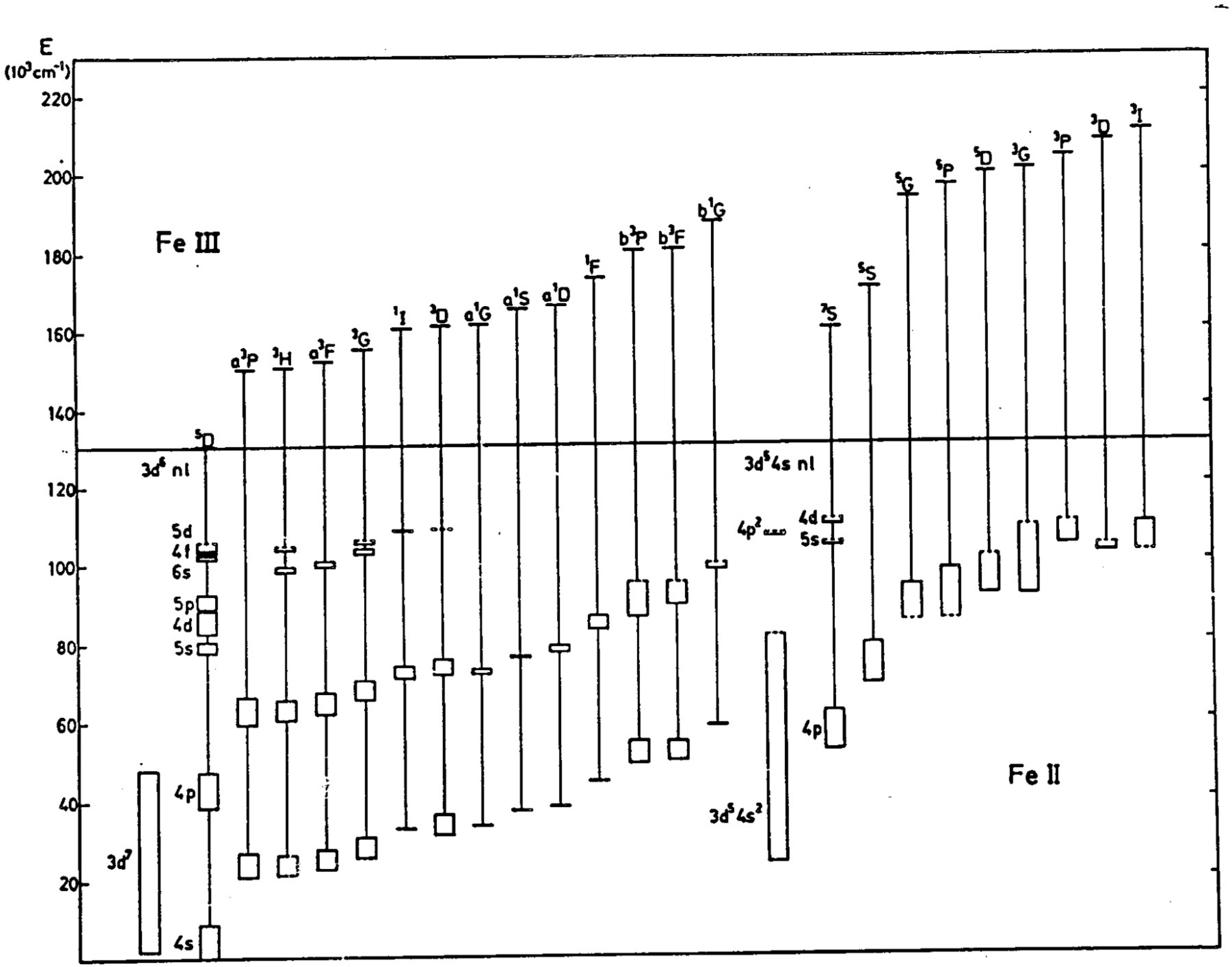
- STELLAR PLASMA DIAGNOSTIC
- ABUNDANCE DETERMINATIONS
- STELLAR SPECTRA MODELLING, ANALYSIS AND SYNTHESIS
- CHEMICAL STRATIFICATION
- SPECTRAL CLASSIFICATION
- NUCLEAR PROCESSES IN STELLAR INTERIORS
- RADIATIVE TRANSFER
- STELLAR OPACITIES

Line shapes enter in the models of radiative envelopes by the estimation of the Rosseland optical depth . If the atmosphere is in macroscopic mechanical equilibrium and with ρ is denoted gas density, the optical depth is

$$\tau_\nu = \int_z^\infty \kappa_\nu \rho \, dz,$$

$$\kappa_\nu = N(A, i)\phi_\nu \frac{\pi e^2}{mc} f_{ij},$$


E
(10³cm⁻¹)
220
200
180
160
140
120
100
80
60
40
20
Fe III
⁵D
3d⁶ nl
5d
4f
6s
5p
4d
5s
4p
4s
3d⁷
a³P
³H
a³F
³G
¹I
³D
a¹G
a¹S
a¹D
¹F
b³P
b³F
b¹G
3d⁵4s nl
4p² ...
4d
5s
⁷S
⁵S
4p
3d⁵4s²
⁵G
⁵P
⁵D
³G
³P
³D
³I
Fe II

E(kK)

4F

E(eV)

- In 1926, Henry Russel published in Astrophysical Journal his article with the analysis of Fe II spectrum resulting in 61 energy levels determined from 214 Fe II spectral lines, stating that "all the lines of astrophysical
- importance have been classified". This statement however, was too optimistic. Now more than 900 Fe II energy levels is known but 50% of individual spectral features in high resolution astronomical spectra is still unclassified.

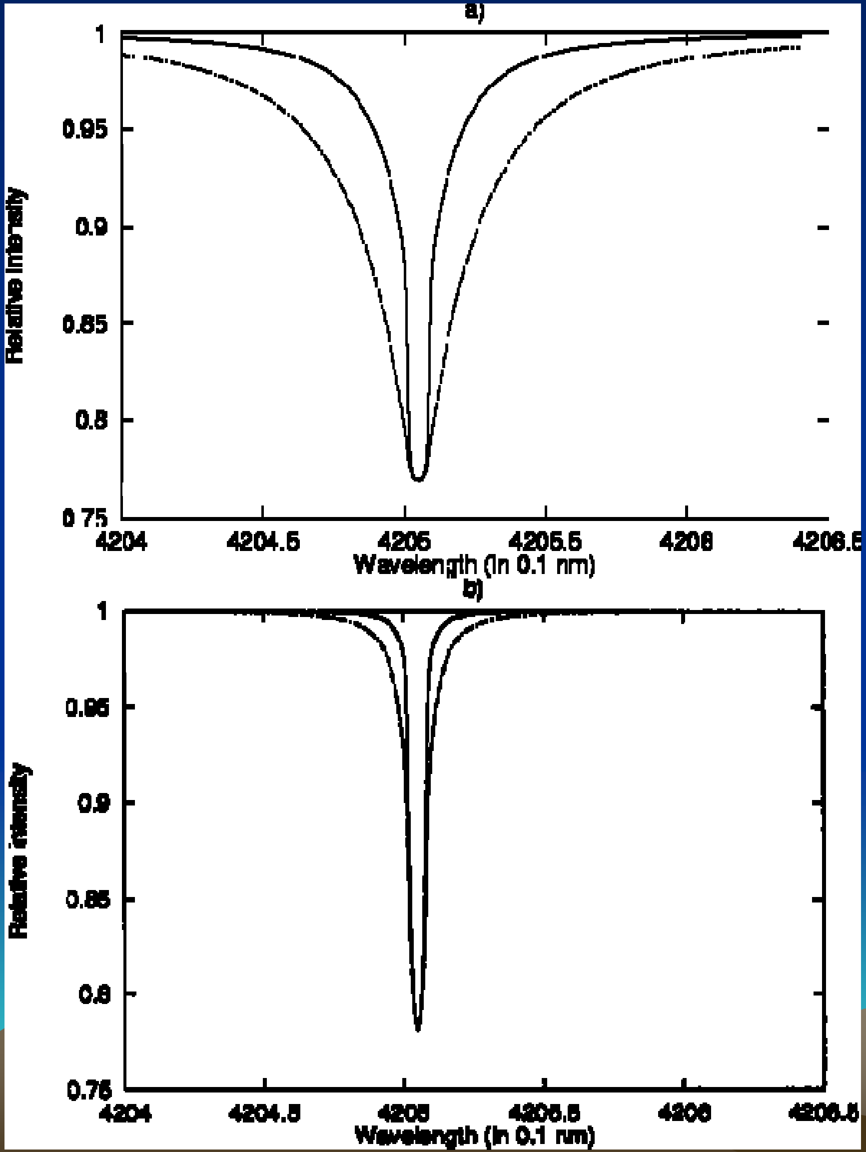
STARK BROADENING ON BELGRADE ASTRONOMICAL OBSERVATORY

- QUANTUM MECHANICAL METHOD
- SEMICLASSICAL PERTURBATION METHOD
- MODIFIED SEMIEMPIRICAL METHOD
- REGULARITIES AND SYSTEMATIC TRENDS

STARK BROADENING ON BELGRADE OBSERVATORY

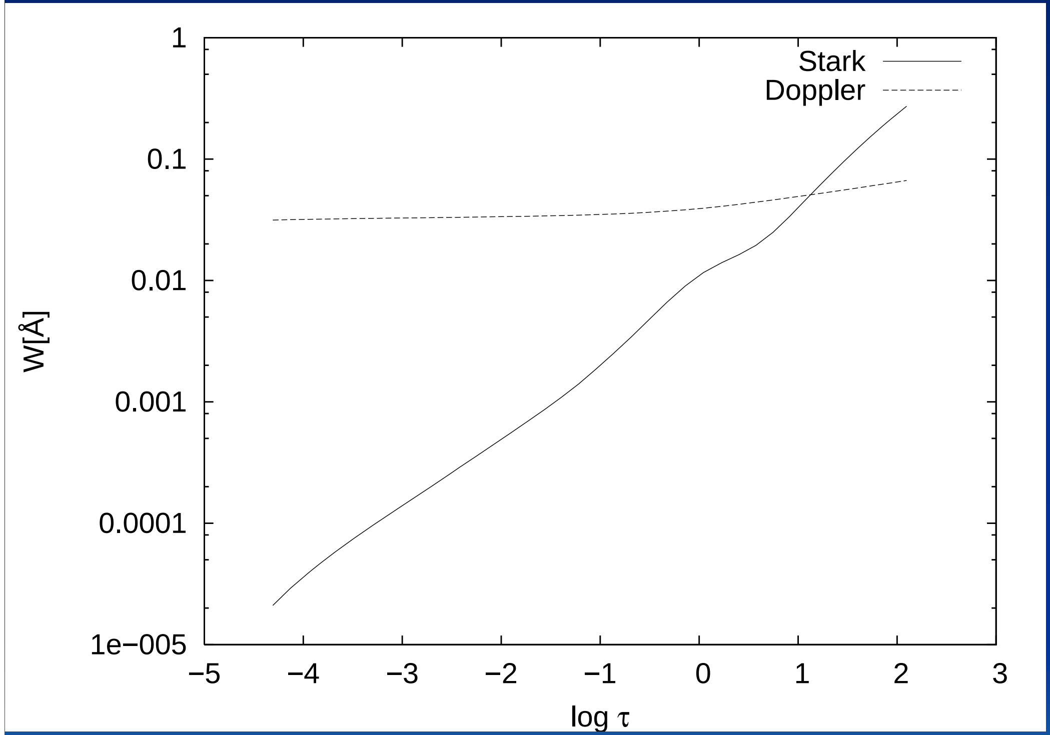
- INVESTIGATION OF THE INFLUENCE OF STARK BROADENING ON PROFILES OF STELLAR SPECTRAL LINES
- STARK BROADENING AND MODELLING, ANALYZIS AND SYNTHEZIS OF STELLAR SPECTRA
- SPECTROSCOPICALLY DETECTABLE INFLUENCES OF COLLISIONAL PROCESSES ON ELECTRON DENSITY IN STELLAR ATMOSPHERES
-

The line profile of Eu II 420.505 nm line synthesized with Stark broadening mechanism taken into account (dashed line) and without it (full line). The calculations have been performed for the atmosphere model with *T*e=9500K and log *g*=4.5. The abundances of europium are a) log(Eu/H)=-5.9 and b) log(Eu/H)=-7.5



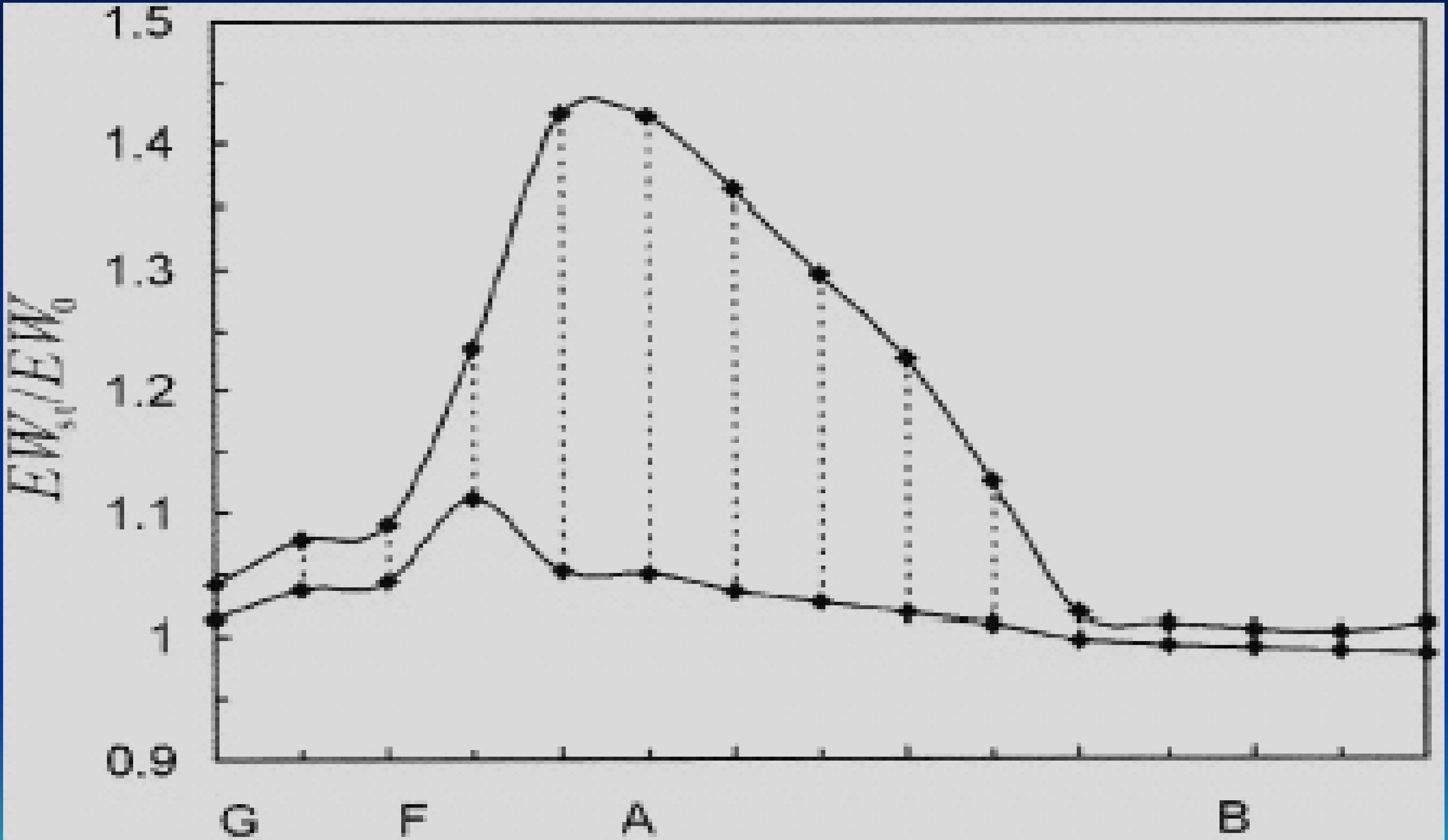
- **Astron. Astrophys. 350, 719–724 (1999)**
- ***The electron-impact broadening effect in CP stars: the case of La II, La III, Eu II, and Eu III lines***
- **L. C. Popovic, M.S. Dimitrijevic, and T. Ryabchikova**

Z. Simić, M. S. Dimitrijević, A. Kovačević, 2009, *New Astronomy Review*, 53, 246.



- Te I 6s 5 S° - 6p 5P (9903.9 Å).
- A STAR OF A SPECTRAL TYPE
- (Teff = 10000 K, log g = 4.5).

Maximum (top line) and minimum (bottom line) of the ratio of the equivalent widths for different types of stars. The maximum EWSt/EW0 and minimum value for all 38 Nd II lines considered are summarized.

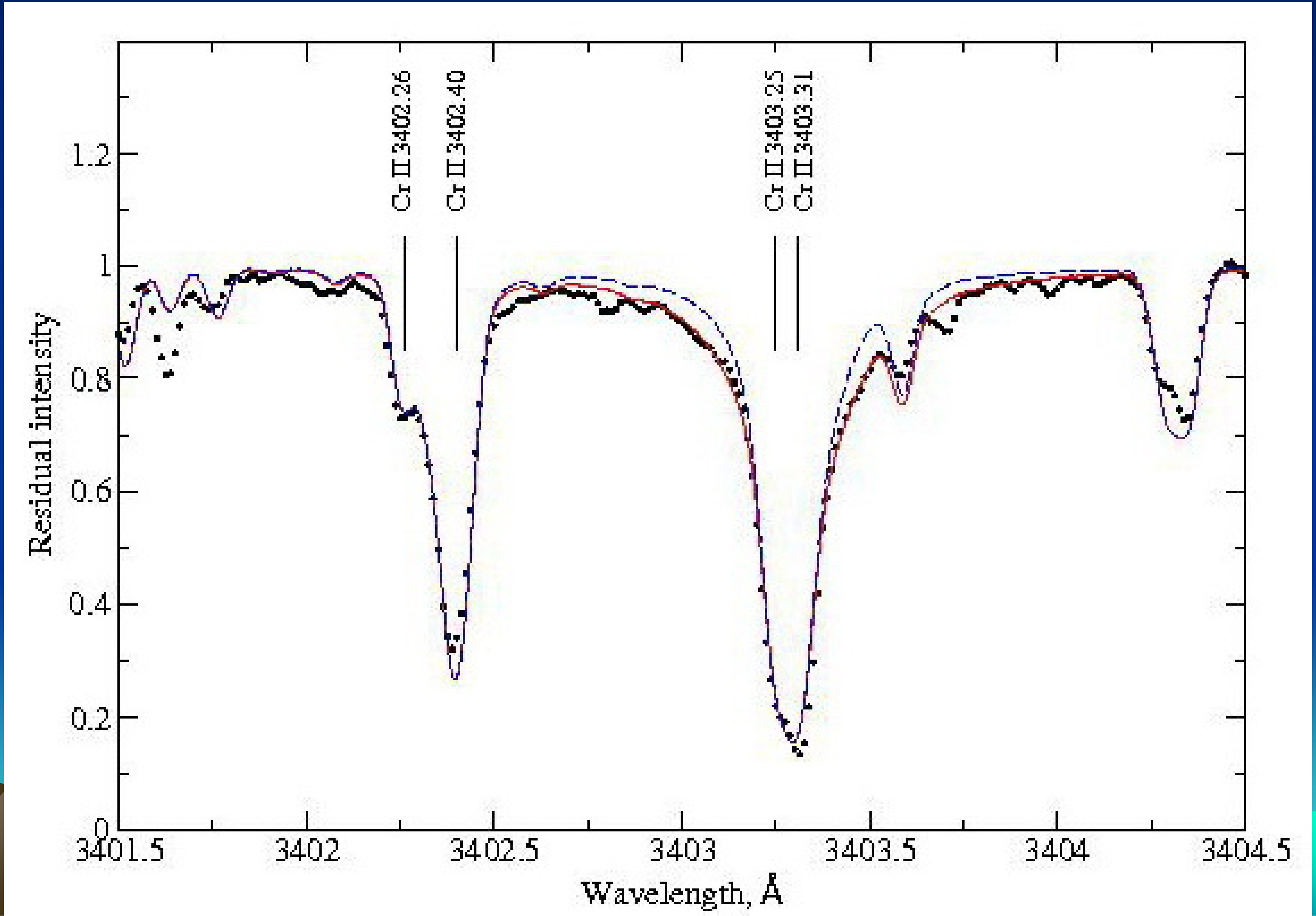


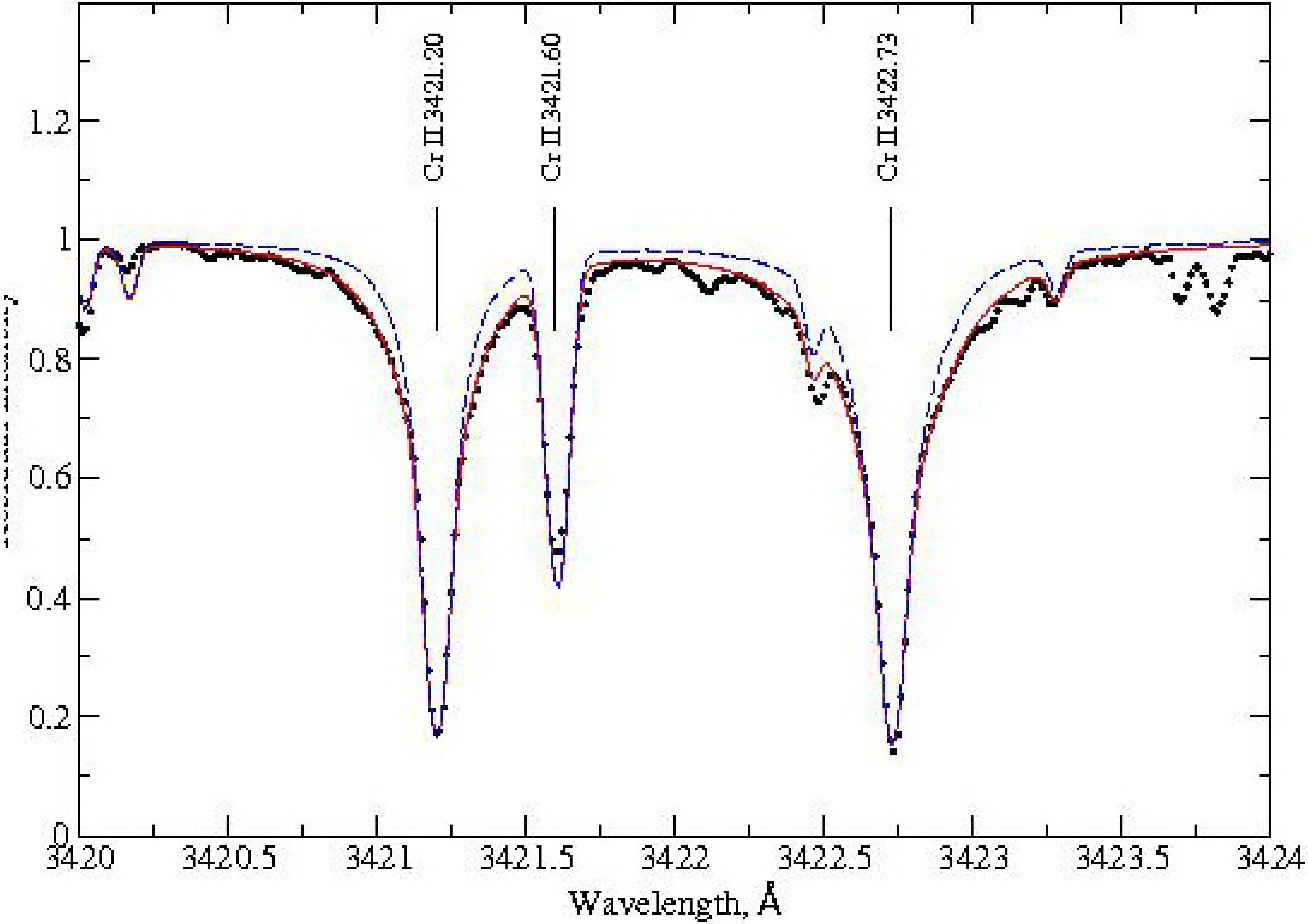
- THE ASTROPHYSICAL JOURNAL SUPPLEMENT SERIES, 135:109-114, 2001
- *STARK BROADENING EFFECT IN STELLAR ATMOSPHERES: Nd II LINES*
- L. C. POPOVIC , S. SIMIC,
- N. MILOVANOVIC, M. S.DIMITRIJEVIC

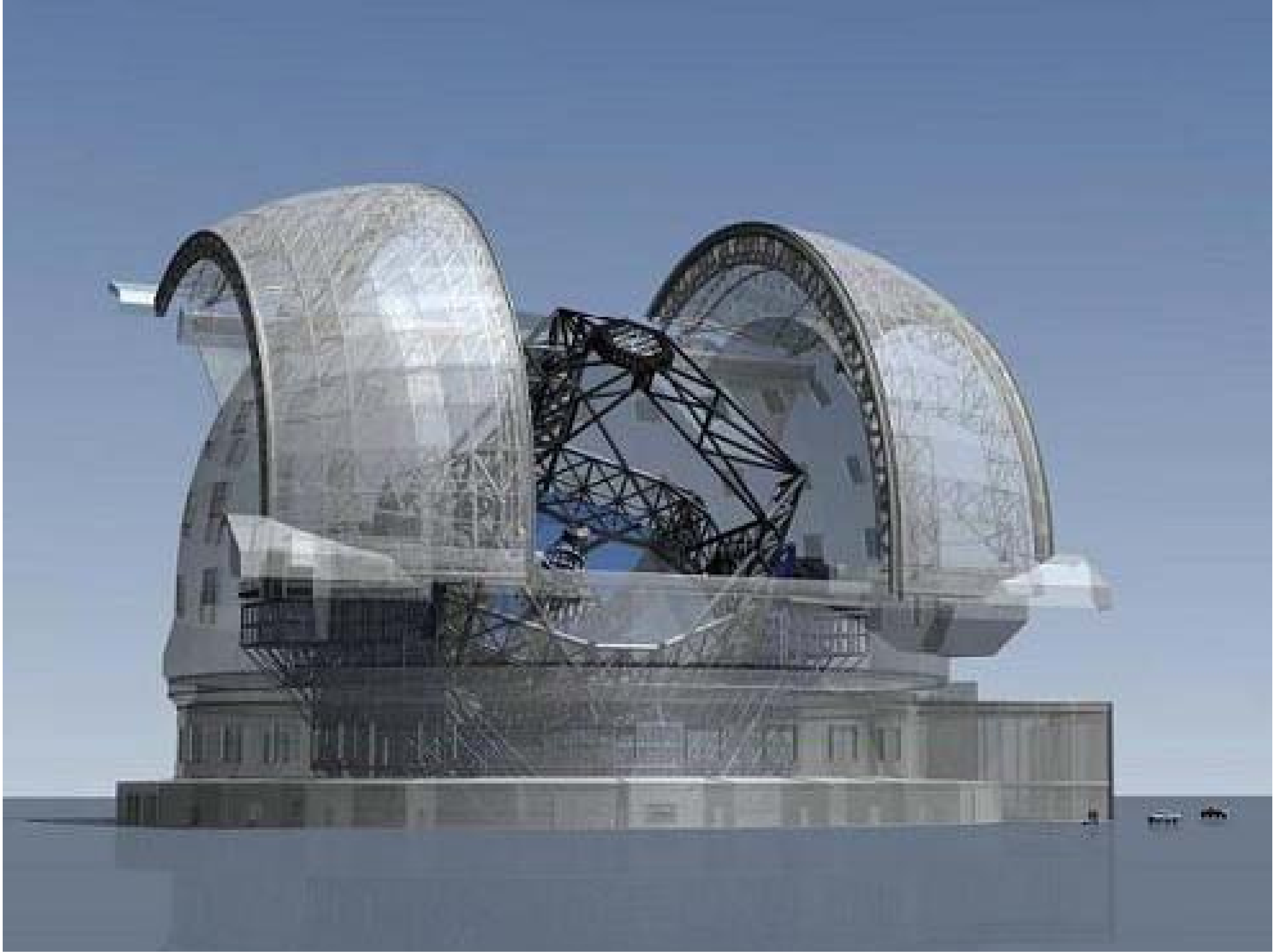
M. S. Dimitrijević, T. Ryabchikova, Z. Simić, L. Č. Popović and M. Dačić, *Astron. Astrophys*., **469**, 681 (2007).

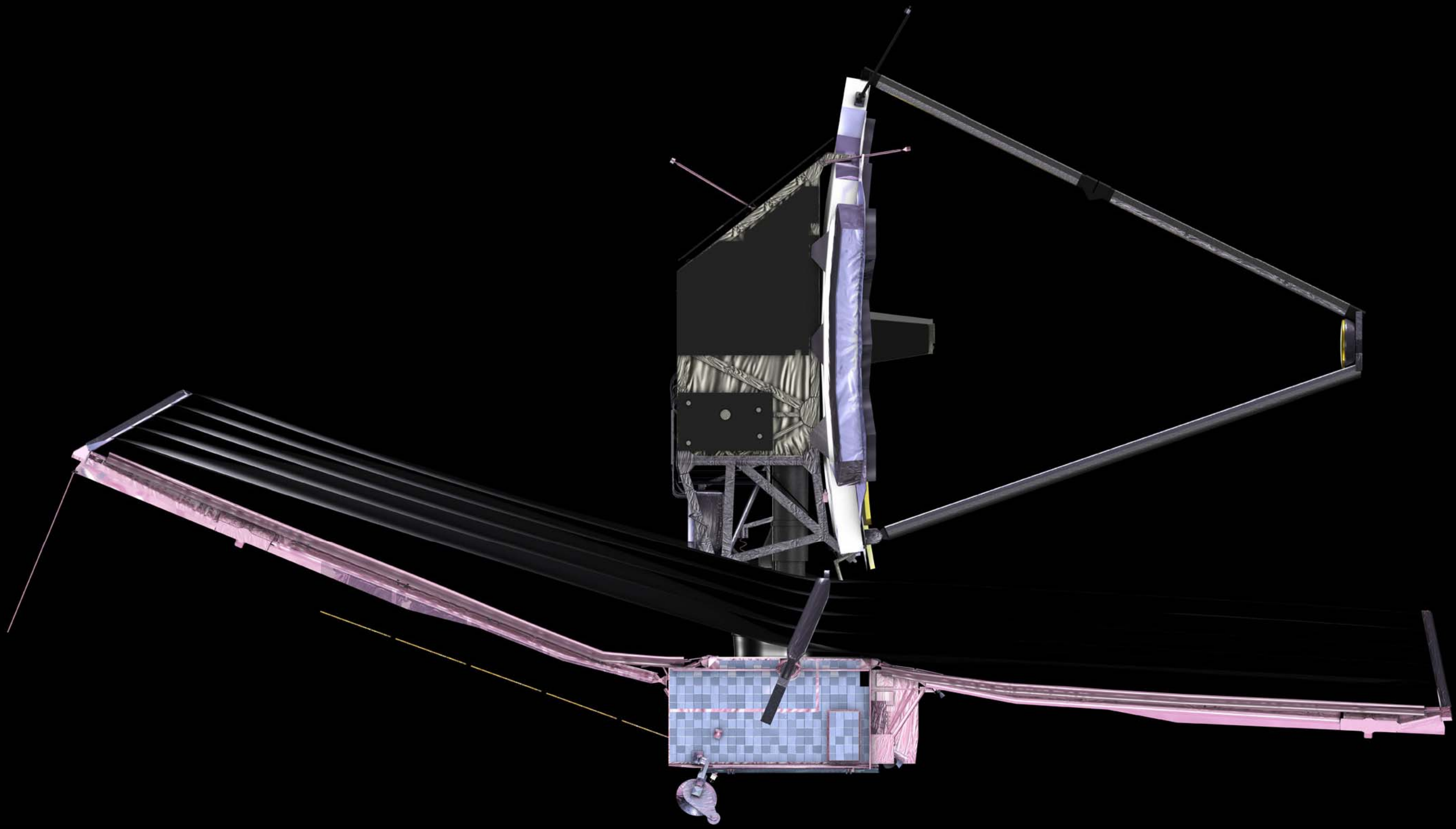
We investigated Stark broadening of Cr II lines in Ap star HD 133792 for which careful abundance and stratification analysis was performed by Kochukov et al. 2006, A&A, 460, 831. For this star Teff=9400 K, log g = 3.7. Code SYNTH3

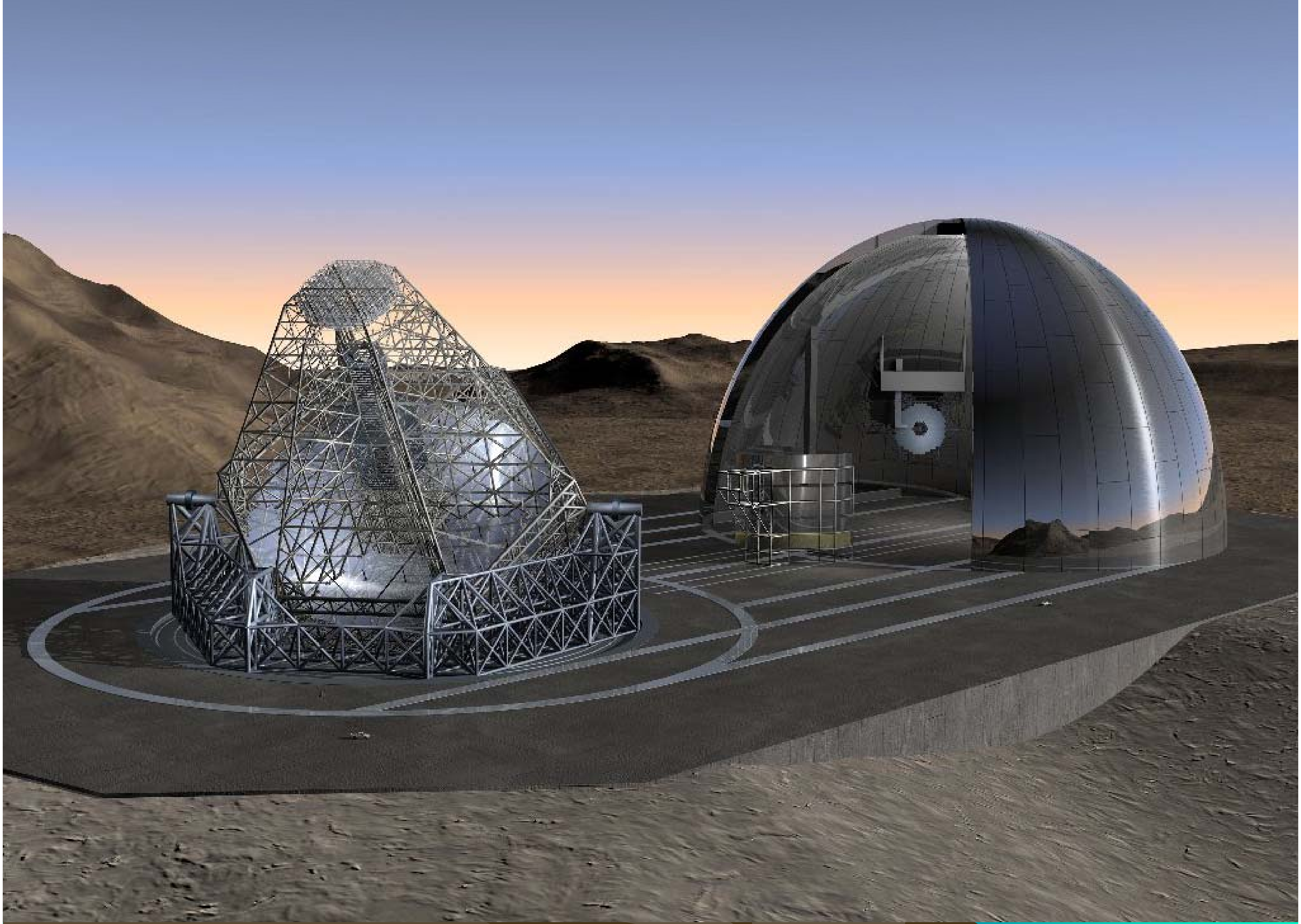
M. S. Dimitrijević, T. Ryabchikova, Z. Simić, L. Č. Popović and M. Dačić, *Astron. Astrophys*., **469**, 681 (2007).




Cr II 3421.20
Cr II 3421.60
Cr II 3422.73
0
0.2
0.4
0.6
0.8
1
1.2
3420
3420.5
3421
3421.5
3422
3422.5
3423
3423.5
3424
Wavelength, Å

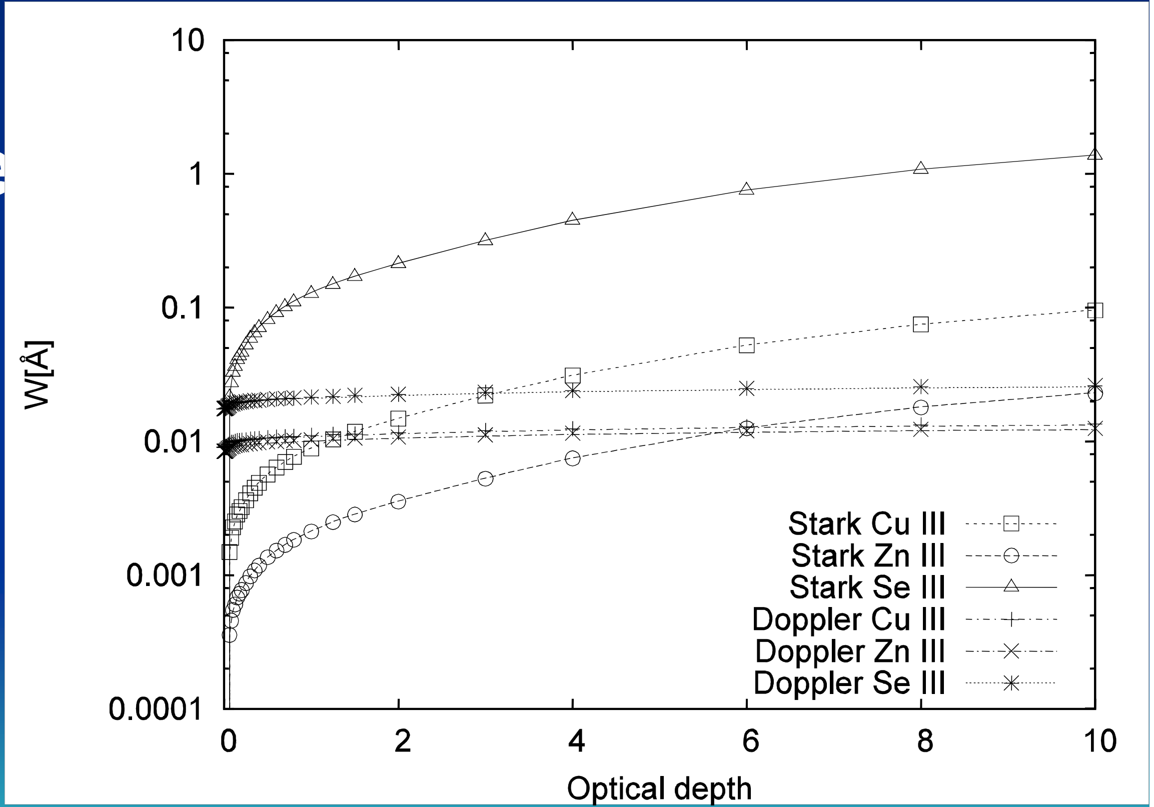






Z. Simić, M. S. Dimitrijević, L. Č. Popović and M. Dačić, *New Astronomy*, 12, 187 (2006).

- Cu III 4s 2F - 4p 2 G^{o} (λ=1774.4 Å), Zn III 4s 3D - 4p 3P^{o} (λ=1667.9 Å) and Se III 4p5s 3 P^{o} - 5p 3D (λ=3815.5 Å)
- DB WHITE DWARF Teff = 15 000 K
- log g = 7,



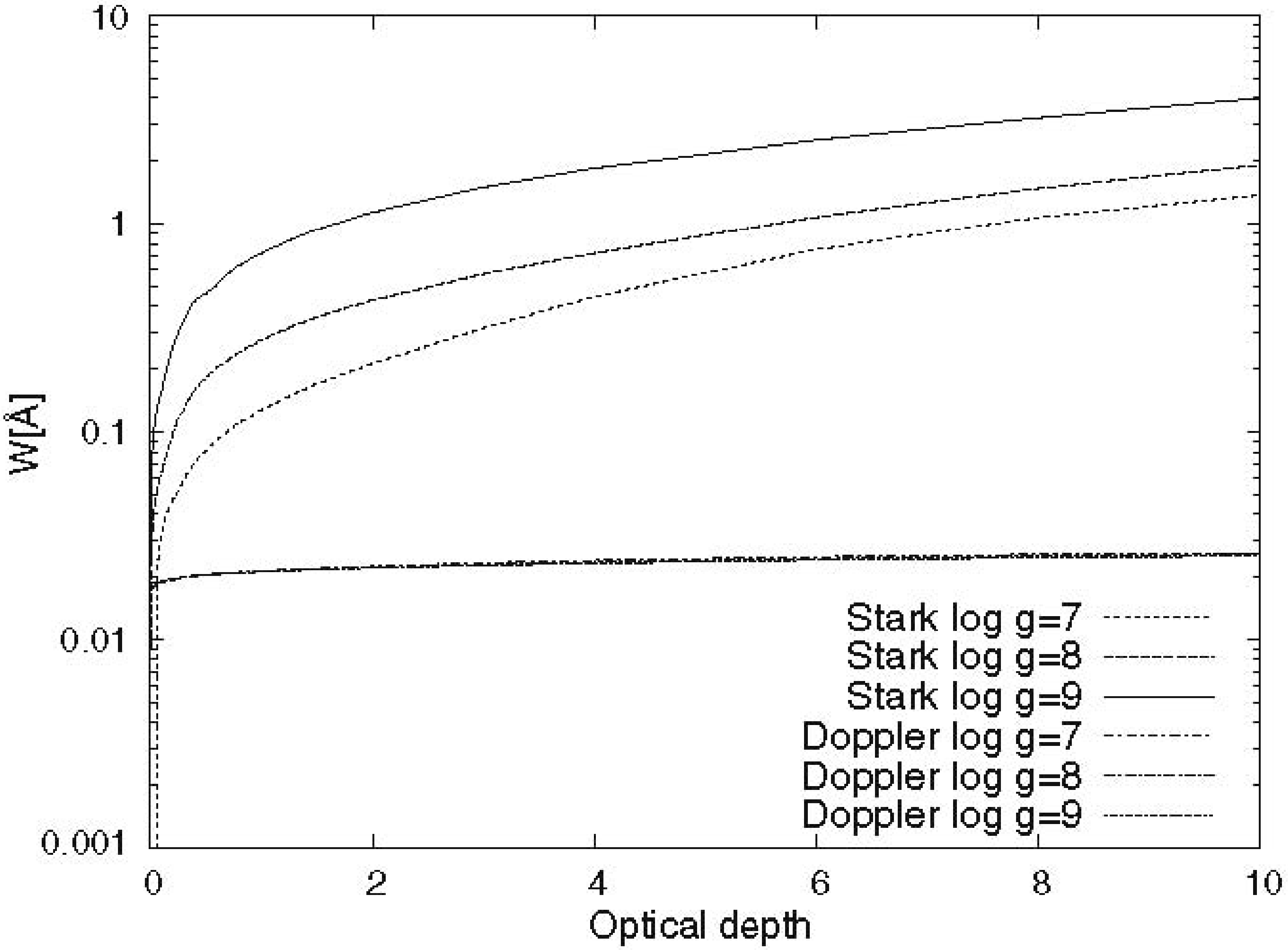


Fig. 4. Thermal Doppler and Stark widths for Se III spectral line 5s $^3P^0$—5p ^3D ($\lambda = 3815.5$ Å) for a DB white dwarf atmosphere model with $T_{eff} = 150,00$ K and $7 \leqslant \log g \leqslant 9$, as a function of optical depth τ_{5150}.

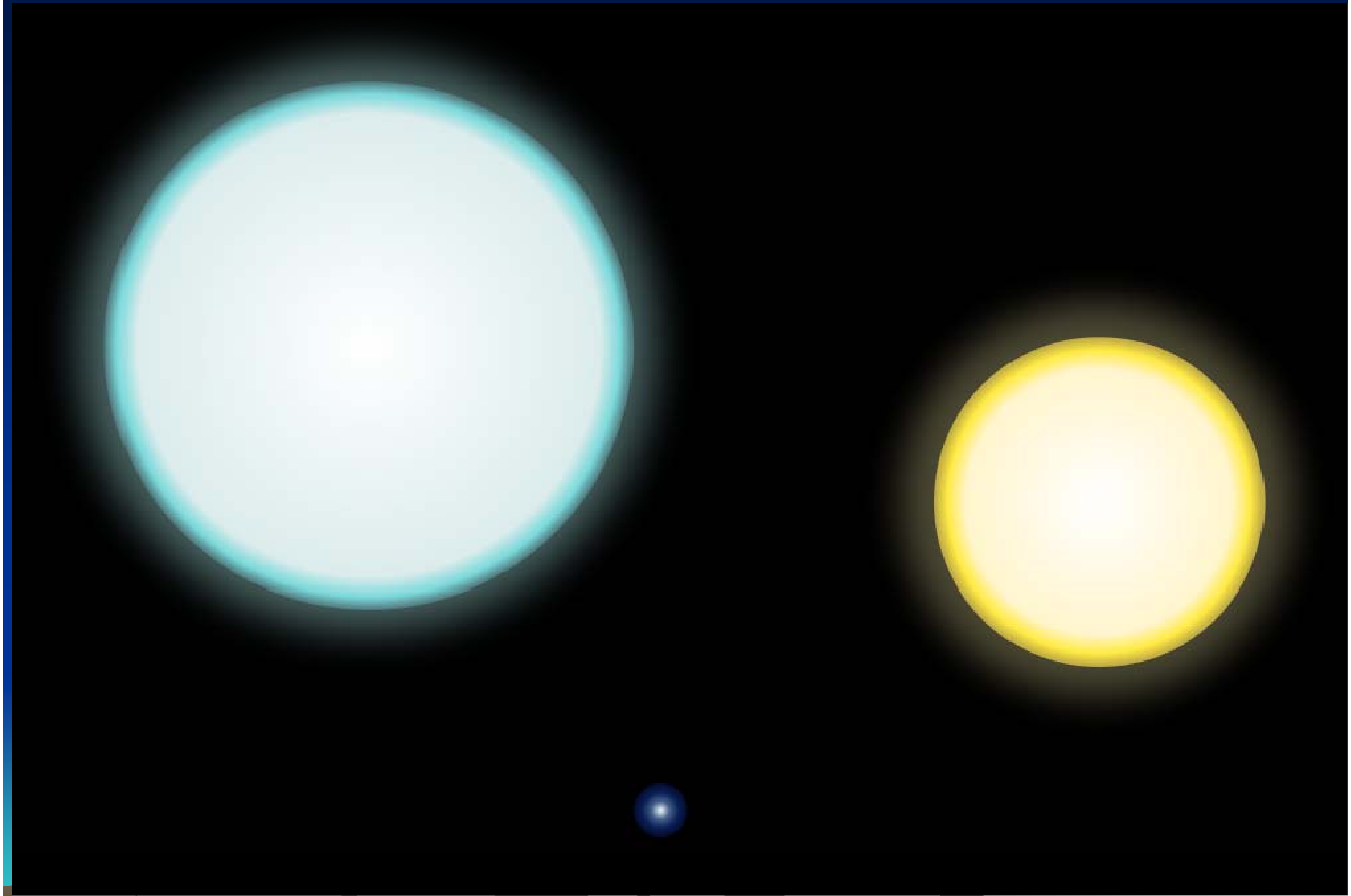
White dwarfs

This will become 97% of stars in our Galaxy

White dwarf with low masses have a helium core,

Those with average masses (majority that we observe) have core of carbon and oxygen

Those with large masses have core of oxygen, neon and magnesium



White dwarfs

The first - 40 Eridani W. Herschel 31.01.1783

The second Sirius B. Bessel forseen in 1844, Alvan Graham Clarck discovered in 1862

The third 1917 van Maanen

1950 known one hundred

1999 around 2000

SDSS more than 9000

White dwarfs

TRADITIONAL DIVISION

DA – HYDROGEN RICH

DB – HELIUM RICH

DB White dwarfs

DO 40 000 K < Teff < 100000 K He II

DB 12 000 K < Teff < 40000 K He I

DQ 4 000 K < Teff < 12000 K C, C_2 Swan band

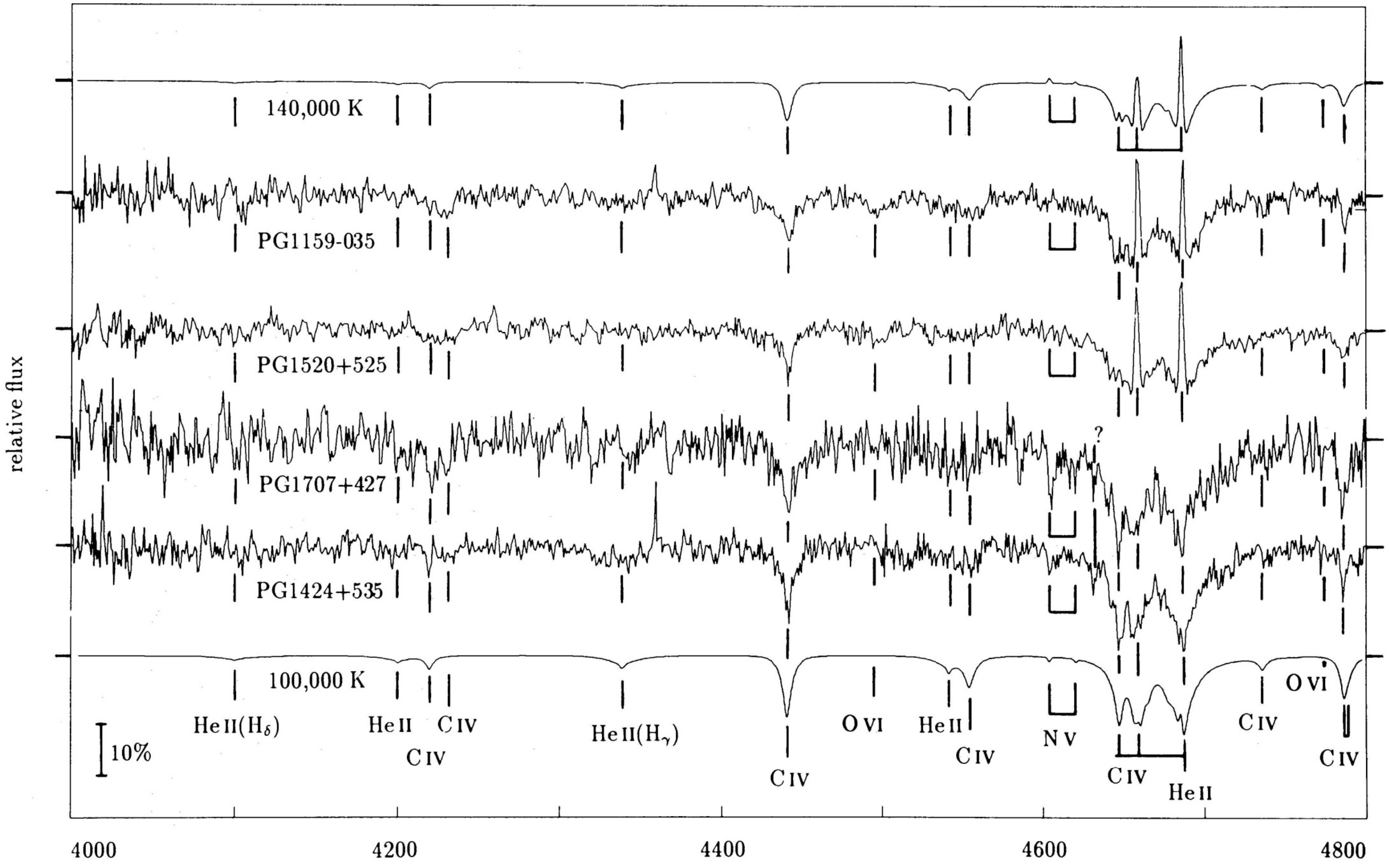
DZ lines of metals, accretion, DAZ, DBZ

DC continuum

- 1979 was discovered prototype of a new class of hot hydrogen defficient degenerate stars PG1159-035

- McGraw J. T., Starrfield S., Liebert J., Green R. F. 1979, Proc. IAU Coll. 53: White dwarfs and variable degenerate stars, H. M. van Horn, V. Weidemann eds., Univ. of Rochester, 377

K. Werner, U. Heber, K. Hunger, 1991, A&A, 244, 437



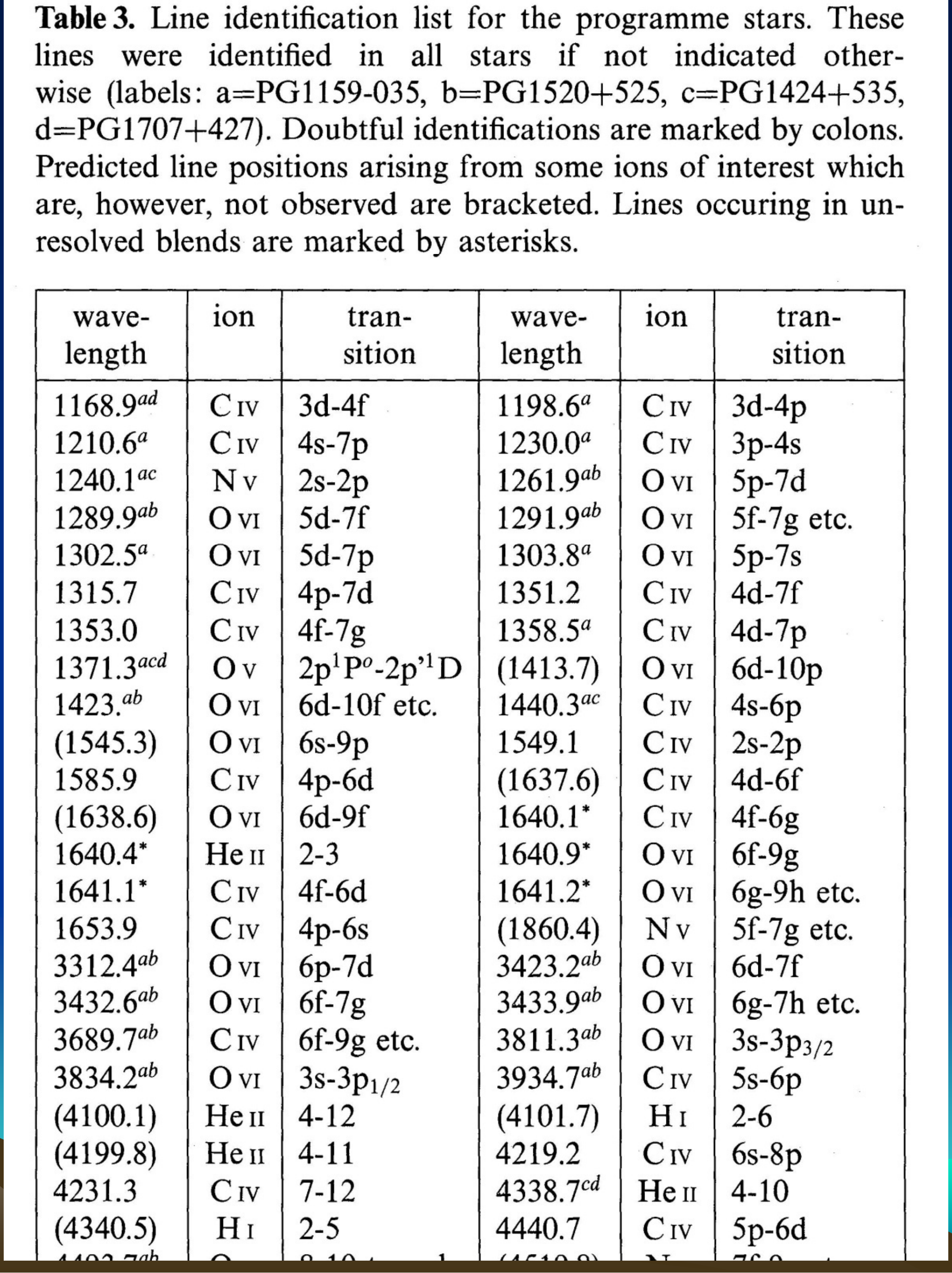


Table 3. Line identification list for the programme stars. These lines were identified in all stars if not indicated otherwise (labels: a=PG1159-035, b=PG1520+525, c=PG1424+535, d=PG1707+427). Doubtful identifications are marked by colons. Predicted line positions arising from some ions of interest which are, however, not observed are bracketed. Lines occuring in unresolved blends are marked by asterisks.

wave-length	ion	tran-sition	wave-length	ion	tran-sition
1168.9^{ad}	C IV	3d-4f	1198.6^{a}	C IV	3d-4p
1210.6^{a}	C IV	4s-7p	1230.0^{a}	C IV	3p-4s
1240.1^{ac}	N V	2s-2p	1261.9^{ab}	O VI	5p-7d
1289.9^{ab}	O VI	5d-7f	1291.9^{ab}	O VI	5f-7g etc.
1302.5^{a}	O VI	5d-7p	1303.8^{a}	O VI	5p-7s
1315.7	C IV	4p-7d	1351.2	C IV	4d-7f
1353.0	C IV	4f-7g	1358.5^{a}	C IV	4d-7p
1371.3^{acd}	O V	2p^{1}P^o-2p'^{1}D	(1413.7)	O VI	6d-10p
1423.^{ab}	O VI	6d-10f etc.	1440.3^{ac}	C IV	4s-6p
(1545.3)	O VI	6s-9p	1549.1	C IV	2s-2p
1585.9	C IV	4p-6d	(1637.6)	C IV	4d-6f
(1638.6)	O VI	6d-9f	1640.1*	C IV	4f-6g
1640.4*	He II	2-3	1640.9*	O VI	6f-9g
1641.1*	C IV	4f-6d	1641.2*	O VI	6g-9h etc.
1653.9	C IV	4p-6s	(1860.4)	N V	5f-7g etc.
3312.4^{ab}	O VI	6p-7d	3423.2^{ab}	O VI	6d-7f
3432.6^{ab}	O VI	6f-7g	3433.9^{ab}	O VI	6g-7h etc.
3689.7^{ab}	C IV	6f-9g etc.	3811.3^{ab}	O VI	3s-3p$_{3/2}$
3834.2^{ab}	O VI	3s-3p$_{1/2}$	3934.7^{ab}	C IV	5s-6p
(4100.1)	He II	4-12	(4101.7)	H I	2-6
(4199.8)	He II	4-11	4219.2	C IV	6s-8p
4231.3	C IV	7-12	4338.7^{cd}	He II	4-10
(4340.5)	H I	2-5	4440.7	C IV	5p-6d

- Atmospheres of PG1159 stars show a mixture of helium carbon and oxygen. The most likely explanation is that these stars experienced a very late thermal pulse that returned them back from white dwarf to the post AGB phase.
- This rather violent event leave the surface composition without hydrogen and in the same time mixes helium with carbon, oxygen and other elements from the envelope

Nugent J. J., Jensen K. A., Nousek J. A. et al. 1983, ApJS, 51, 1

- Nugent et al. (1983) discover H 1504+65 a PG 1195 faint blue star which is not only hydrogen defficient but also helium defficient. Atmosphere is composed from carbon and oxygen by equal amount.
- Teff is 170000 K ± 20000 K and this is the hottest known star or “bare core of the former AGB star” according to Werner et Wolff (1999).

M. Fontaine, P. Chayer, C. M. Oliveira, F. Wesmael, G. Fontaine, 2008, ApJ, 678, 394

- FUSE – Far Ultraviolet Spectroscopic Explorer satellite (H. W. Moss et al. 2000, ApJ, 538, L1) provided astronomers with high resolution spectra of hot evolved stars within the wavelength range 907 – 1187 Ǻ. Fontaine et al. (2008) note as well that FUSE range includes “high density of transitions associated with numerous ionization levels of several elements such as:

- C, N, O, Si, S, P, Cl, Ne, Ar, V, Mn, Cr, Fe, Co, Ni, Ge, As, Se, Zr, Te, I and Pb among others.”

Observations and analyses of hot white dwarfs, PG 1159 stars, hot B subdwarfs, post AGB (Asymptotic Giant Branch) objects such as CSPNs (Central Stars of Planetary Nebulae) have been performed by FUSE

Post AGB objects

- Stars which experienced complete Hydrogen, helium but not carbon burning, form a continuous sequence of bright red giants more luminous than RGB – Red Giants Branch formed by stars with electron-degenerate helium cores. Such stars, with cores in which the dominant elements are heavier than helium are called AGB – Asympotic Giant Branch stars. Often this reffers only to carbon-oxygen cores and stars with heavier cores are called SAGB (Super AGB) stars

- Depending on mass and composition of its main sequence precursor the initial mass of helium-exosted core may be from 0.5 up to maximal 1.1 solar masses, and initial carbon-exosted cores are from 1.1 up to 1.37 solar masses

M. Fontaine, P. Chayer, C. M. Oliveira, F. Wesmael, G. Fontaine, 2008, ApJ, 678, 394

- Fontaine et al. (2008) performed with the help of FUSE, an analysis of hot hydrogen rich subdwarf GD 605 (classified as sdO4:He2 type)

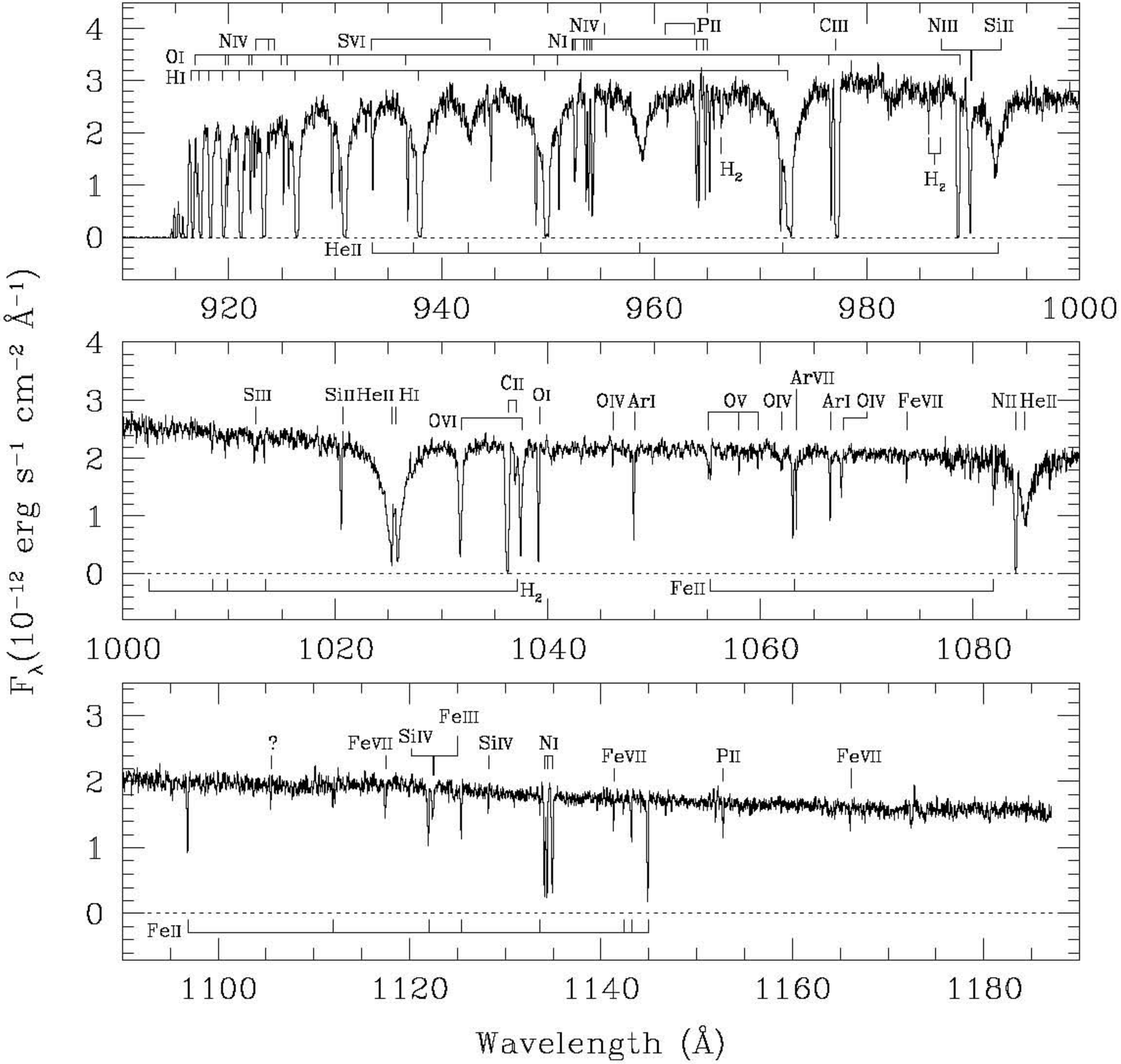


FIG. 1.—*FUSE* spectrum of GD 605. The main features present in the spectrum are labeled. This spectrum was obtained by merging the SiC1B, LiF1A, SiC2B, LiF2A, and LiF1B segments.

In Rauch et al. 2007, A&A, 470, 317 was pointed out that line broadening data fore many species and their ions are missing in the literature. Moreover, some existing are provided within the insufficient temperature and density ranges and extrapolation to the plasma conditions in line forming regions introduces additional errors.

K. Werner, U. Heber, K. Hunger, 1991, A&A, 244, 437.

- STARK BROADENING FOR PG 1195 STARS
- 1. Problem: Perturbing ions: Besides protons, He III, C V and O VII are present
- 2. Transition between linear and quadratic Stark effect
- Werner et al. assume: For C IV, N V, O VI linear Stark effect is dominant

- Empirical correction factor is introduced to eliminate overestimation.

- Their method they name “Modified Holtsmark Theory” and apply The Holtsmark statistical pressure broadening theory according to Unsold (1968, Eq. 82.23b)

- They obtain for absorption cross section for the Stark wing of a line transition ij

- $\sigma_{ij}\ (\Delta\lambda)=(\pi e^2/mc^2)\lambda^2(f_{ij}/s_nF_0)\ U(\Delta\lambda/s_nF_0)$
- s_n is a measure for the Stark width
- $s_n=0.0192\lambda^2\{n_{up}(n_{up}-1) + n_{low}(n_{low}-1)\}/Z$

- F_0 is the normal field strength calculated from the actual ion mixture
- $F_0 = 2.61e(\Sigma Z_{ion}{}^{3/2}n_{ion})^{2/3}$

- Here Z_{ion}, n_{ion} are charges and occupation densities of the perturbing ions.

- U(b) is integral from b to infinity of W(b)/2b
- Where W(b) is Holtsmark's distribution function.

- The obtained wing is added to the Doppler profile and then normalized.
- In order to compensate overestimation of the Stark width s_n is divided by empirical correction factor δ.

R. Hamdi, N. Ben Nessib, N. Milovanović, L. Č. Popović, M. S. Dimitrijević and S. Sahal-Brécho, *MNRAS*, 387, 871 (2008).

- Si VI 2p4(3P)3s 2P-2p4(3P)3p 2 D^o (*λ* = 1226, 7Å)
- DO WHITE DWARFS Teff = 50 000–100 000 K and log g = 8.

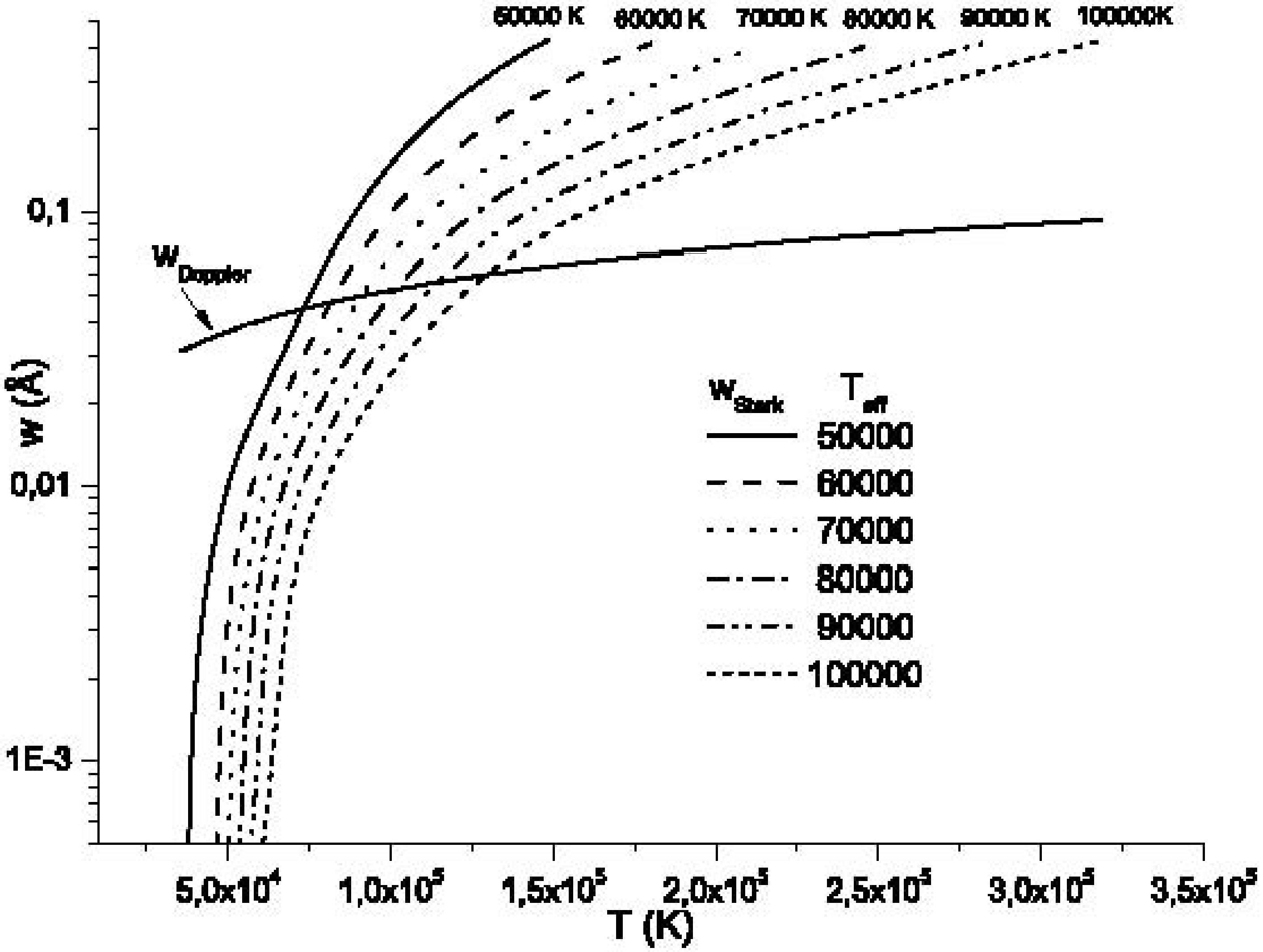


Figure 1. Stark and Doppler widths for Si VI $2p^4(^3P)3s\ ^2P$-$2p^4(^3P)3p\ ^2D^\circ$ ($\lambda = 1226,\ 7$ Å) spectral line as a function of atmospheric layer temperatures. Stark widths are shown for six atmospheric models with effective temperature $T_{\rm eff} = 50\,000$–$100\,000$ K and $\log g = 8$.

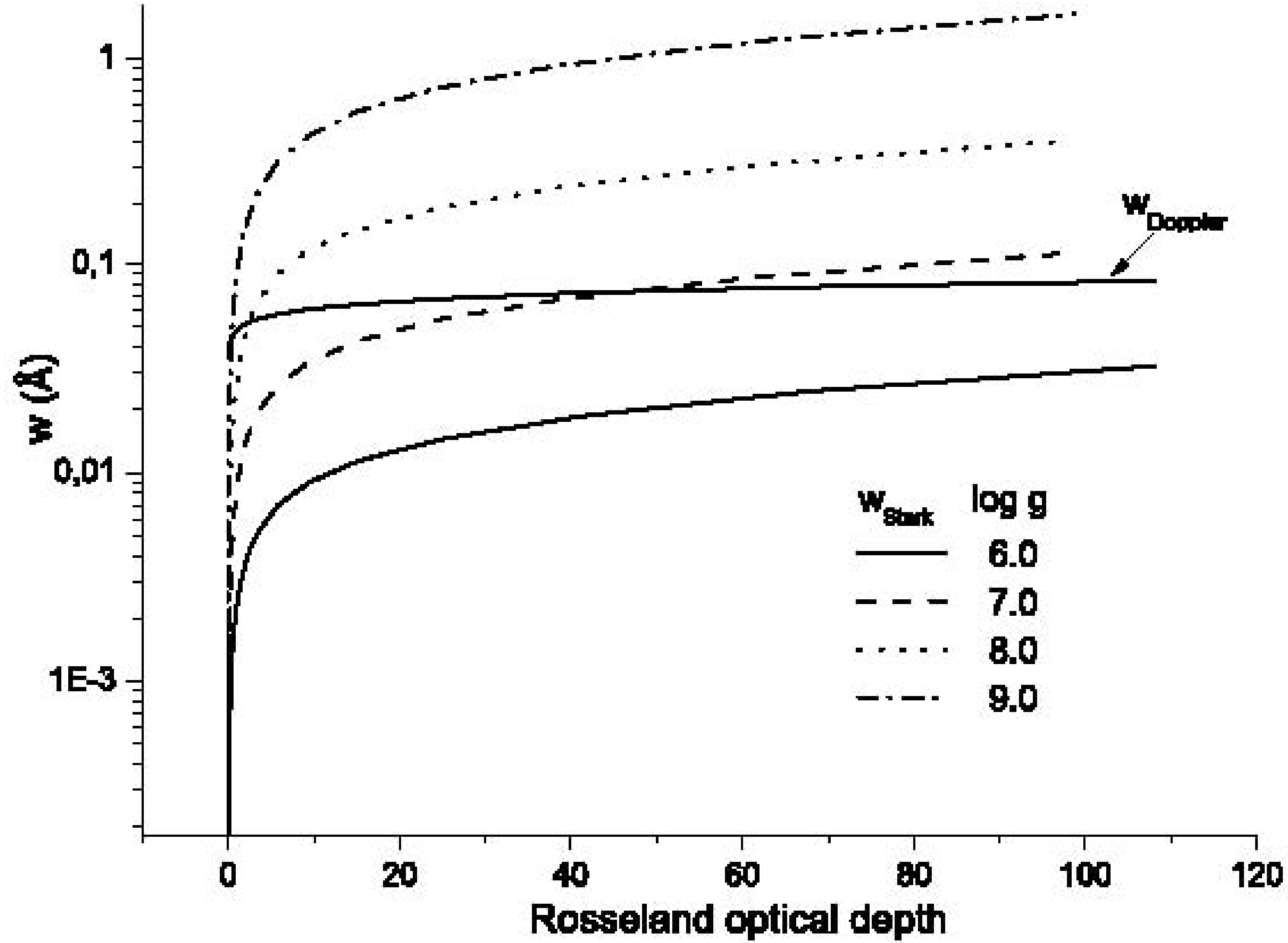


Figure 4. Stark and Doppler widths for Si VI $2p^4(^3P)3s\ ^2P$-$2p^4(^3P)3p\ ^2D^\circ$ ($\lambda = 1226,7$ Å) spectral line as a function of Rosseland optical depth. Stark widths are shown for four values of model gravity $\log g = 6$–9, $T_{\rm eff} = 80\,000$ K.

- DQ 4 000 K < Teff < 12 000 K C, C_2 Swan band
- Liebert et al. 2003 found DQ with C II lines (Teff 12000 -13000 K)
- Dufour et al investigate in SDSS and find hot DQ stars with Teff 18 000 – 24 000 K without lines of H and He and mostly with C II lines.

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LETTERS

White dwarf stars with carbon atmospheres

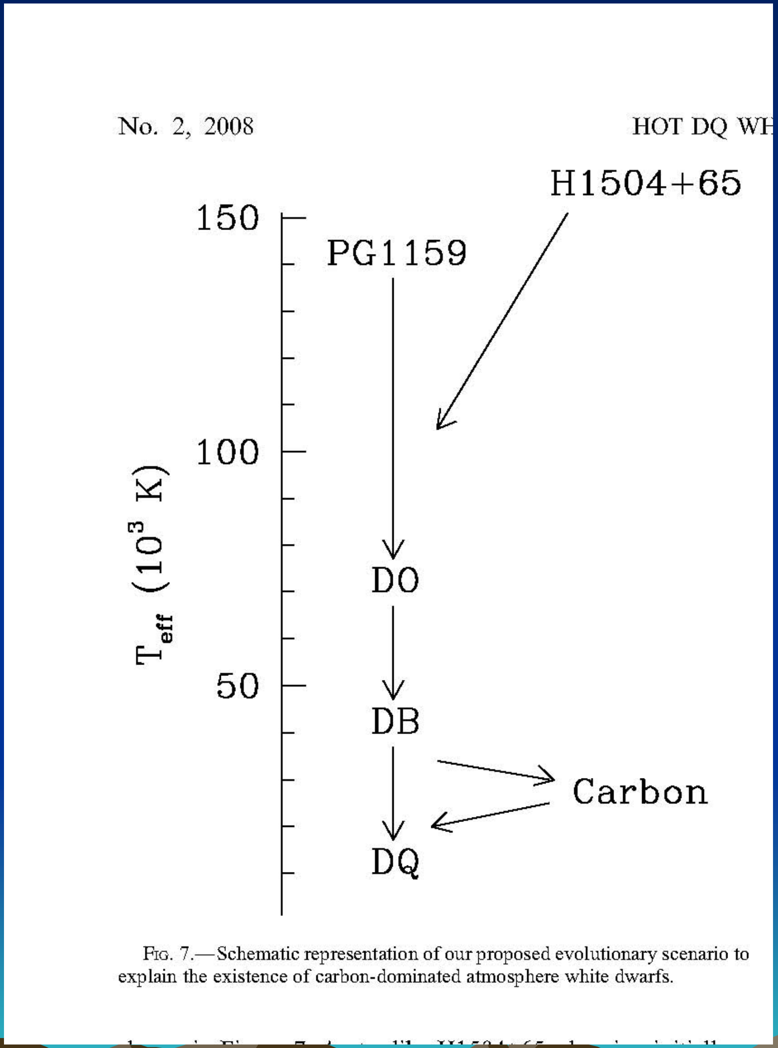
P. Dufour[1], J. Liebert[1], G. Fontaine[2] & N. Behara[3]

White dwarfs represent the endpoint of stellar evolution for stars with initial masses between approximately 0.07 and 8–10$M_\odot$, where $M_\odot$ is the mass of the Sun (more massive stars end their life as either black holes or neutron stars). The theory of stellar evolution predicts that the majority of white dwarfs have a core made of carbon and oxygen, which itself is surrounded by a helium layer and, for ~80 per cent of known white dwarfs, by an additional hydrogen layer[1–3]. All white dwarfs therefore have been traditionally found to belong to one of two categories: those with a hydrogen-rich atmosphere (the DA spectral type) and those with a helium-rich atmosphere (the non-DAs). Here we report the discovery of several white dwarfs with atmospheres primarily composed of carbon, with little or no trace of hydrogen or helium. Our analysis shows that the atmospheric parameters found for these stars do not fit satisfactorily in any of the currently known theories of post-asymptotic giant branch evolution, although these objects might be the cooler counterpart of the unique and extensively studied PG 1159 star H1504+65 (refs 4–7). These stars, together

that these stars had thinner outer helium envelopes so th
occurred earlier in the cooling sequence. These hig
polluted white dwarfs are expected to be massive, so i
that they might represent the missing high-mass tail of
distribution[14].

Thus, it is with this scientific rationale in mind that
with the calculation of the appropriate atmospheric mo
objects. Because the continuum opacity of heavy elemen
be negligible for these objects, these new models have
with the latest C and O photoionization cross-sectic
Opacity Project[15]. Although the analysis of the co
($T_{\mathrm{eff}} < 15{,}000$ K) is straightforward (results will be pr
where; manuscript in preparation), we quickly realized
bination of carbon and helium could successfully re
observed features (mostly C II lines) in the optical spe
hottest ones by assuming a helium-dominated atmosp
such models predict the presence of a strong He I $\lambda = 4{,}4$
not observed spectroscopically in our sample of hot

P. Dufour, G. Fontaine, J. Liebert, G. D. Schmidt, N. Behara, 2008, ApJ, 683, 978



No. 2, 2008 HOT DQ WH

FIG. 7.—Schematic representation of our proposed evolutionary scenario to explain the existence of carbon-dominated atmosphere white dwarfs.

- The origin of H-deficient stars: late helium shell flash in which white dwarf or post AGB star reignites helium shell burning and associate envelope mixing and mass loss eliminates hydrogen.

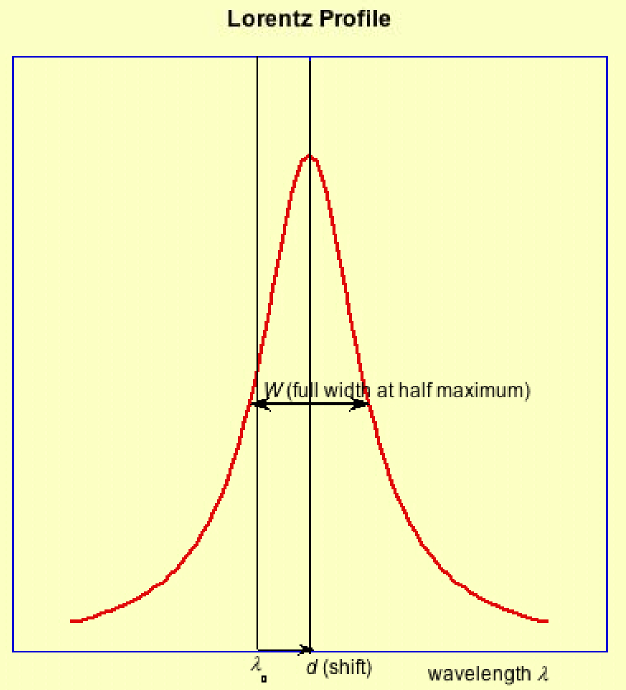
STARK-B

Database for "Stark" broadening of isolated lines of atoms and ions in the impact approximation

S. Sahal-Bréchot*, M.S. Dimitrijević**(scientists responsibles of Stark-b)
and N. Moreau*(Research engineer)
**Observatoire de Paris, LERMA, France*
*** Astronomical Observatory of Belgrade, Serbia*

Calculated widths and shifts contained in more than **100 publications** (1984-2009)

- **Theory and Numerical code** created by S Sahal-Bréchot *(1969 first version, 1974 complex atoms, 1977 addition of Feshbach resonances for ions):* ***SCP*** *(about 6-8 basic papers)*
- **Updated** by M.S. Dimitrijević and S. Sahal-Bréchot
- **Accuracy** : about 20%, sometimes better, sometimes less
- **More than 1500 citations** (ADS) for the whol work



80% of the data are currently implemented but the database has been opened since september 2008

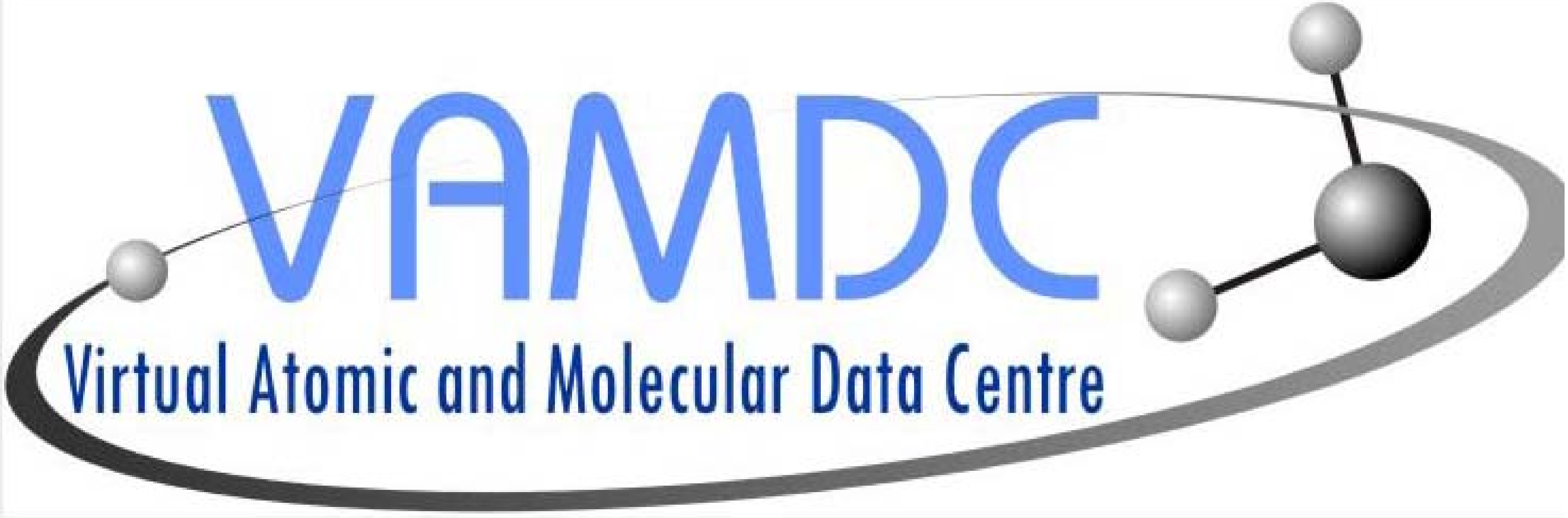
STARK-B

- http://stark-b.obspm.fr/
- This database is devoted to modellisation and spectroscopic diagnostics of stellar atmospheres and envelopes. In addition, it is also devoted to laboratory plasmas, laser equipments and technological plasmas.

STARK B ENTERS VAMDC AND SerVO

- FP 7 PROJECT
- VIRTUAL ATOMIC AND MOLECULAR DATA CENTER,
- P.I. MARIE LISE DUBERNET

- SERBIAN VIRTUAL OBSERVATORY



VAMDC

Virtual Atomic and Molecular Data Centre

Virtual Atomic and Molecular Data Center

Virtual Atomic and Molecular Data Center (VAMDC) is an European FP7 project with aims

-To build a secure, flexible and interoperable e-science environment based interface to the existing Atomic and Molecular databases

VAMDC

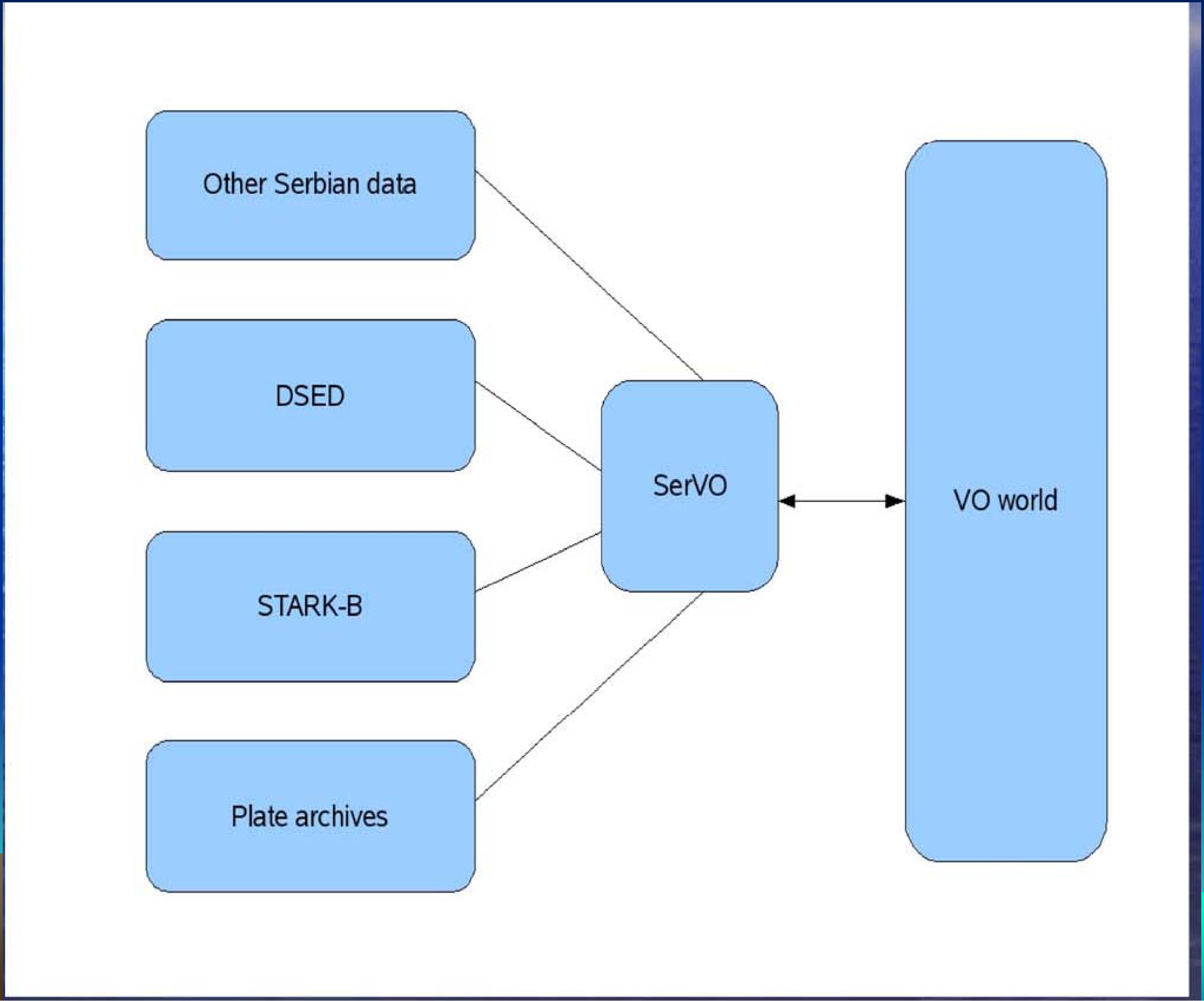
-To coordinate groups involved in the generation, evaluation, and use of atomic and molecular data.

-To provide a forum for training of potential users .

SERBIAN VIRTUAL OBSERVATORY - SerVO

- Project 13022 from April 2008
- Leader DARKO JEVREMOVIĆ
- Main goals
- - Digitization and publishing in VO photographic plates from archive of AOB
- Mirror for STARK-B
- Mirror for DSED
- http://www.servo.aob.rs/~darko

Serbian Virtual Observatory



THANK YOU FOR ATTENTION