

- **STARK BROADENING
AND WHITE DWARFS**

**Milan S. Dimitrijević^{1,2}, Andjelka Kovačević³,
Zoran Simić¹, Sylvie Sahal-Bréchet²,
Nebil Ben Nessib⁴**

¹Astronomical Observatory, Belgrade, Serbia

²Observatoire de Meudon, Paris, France

³Faculty of Mathematics

⁴INSAT, Tunis, Tunisia



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 $T=10^{+6}-10^{+7}K$
- $N_e=10^{+22}-10^{+24}cm^{-3}$, white dwarfs, hot stars, up to other extreme conditions :
- FOR RADIO RECOMBINATION LINES FROM
- H I ($T=50K$) AND H II ($T=10000K$) REGIONS $N_e = 1-1000 cm^{-3}$

- **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:

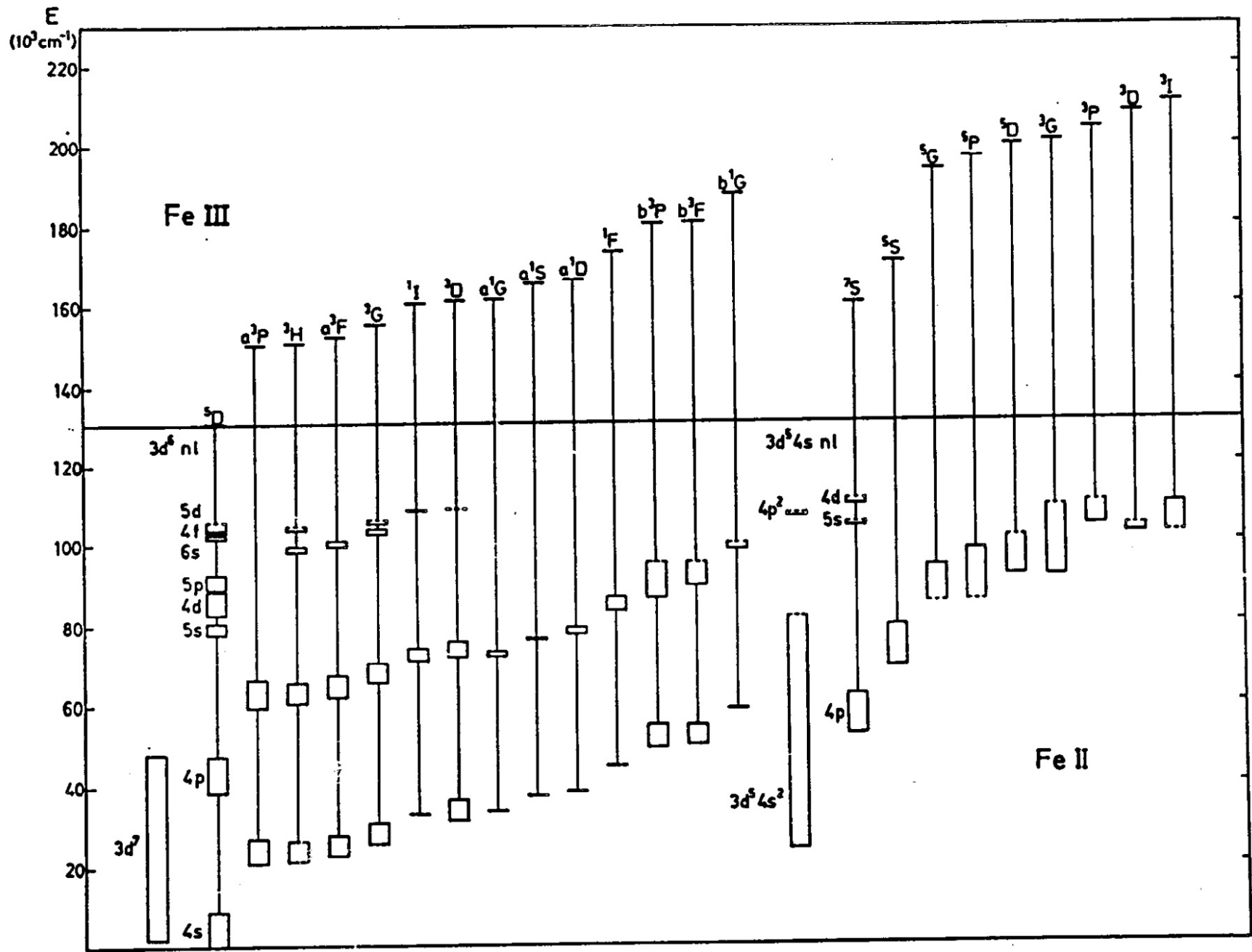
- STELLAR PLASMA DIAGNOSTIC**
- ABUNDANCE DETERMINATIONS**
- STELLAR SPECTRA MODELLING,
ANALYSIS AND SYNTHESIS**
- CHEMICAL STRATIFICATION**
- SPECTRAL CLASSIFICATION**
- NUCLEAR PROCESSES IN STELLAR
INTERIORS**
- RADIATIVE TRANSFER**
- STELLAR OPACITIES**

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



$$\tau_{\nu} = \int_{\mathbf{z}}^{\infty} \kappa_{\nu} \rho \, d\mathbf{z},$$

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



$E(\text{kK})$

$E(\text{eV})$

- 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

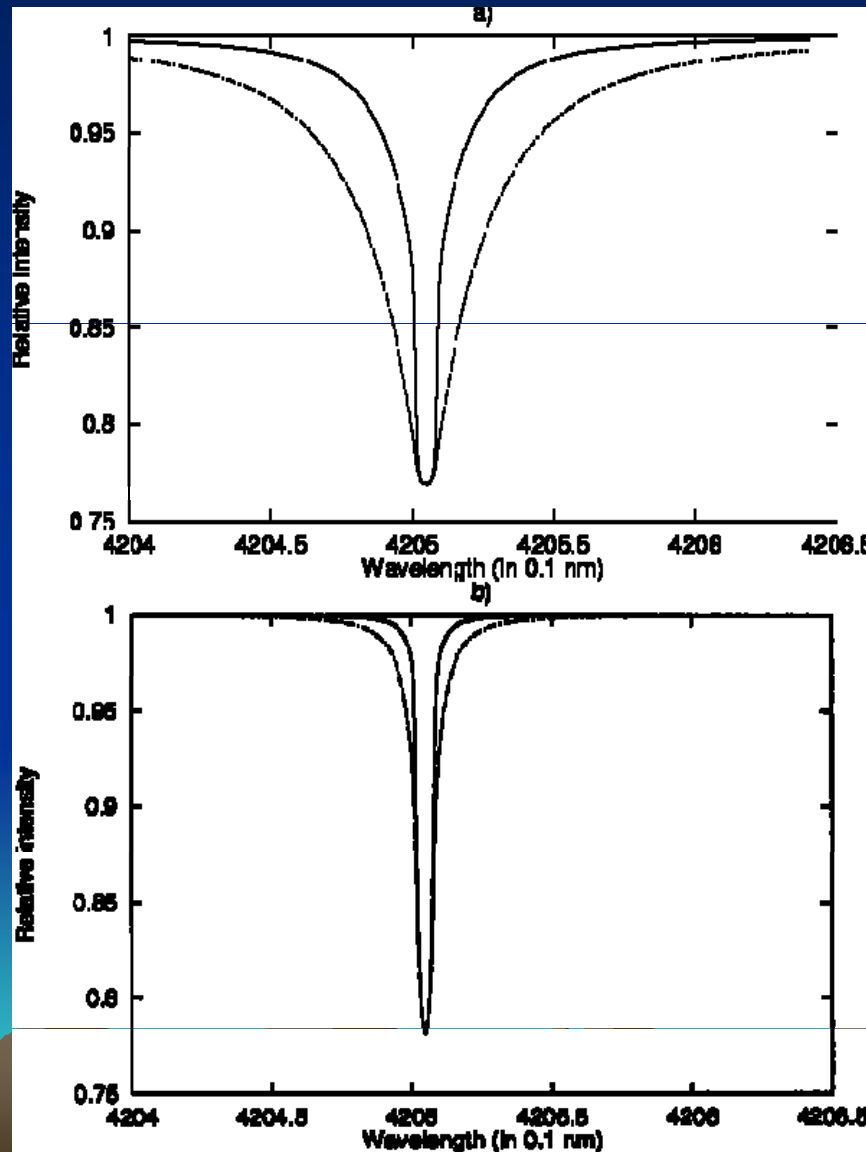
- **QUANTUM MECHANICAL METHOD**
- **SEMICLASSICAL PERTURBATION
METHOD**
- **MODIFIED SEMIEMPIRICAL METHOD**
- **REGULARITIES AND SYSTEMATIC
TRENDS**



STARK BROADENING ON BELGRADE OBSERVATORY

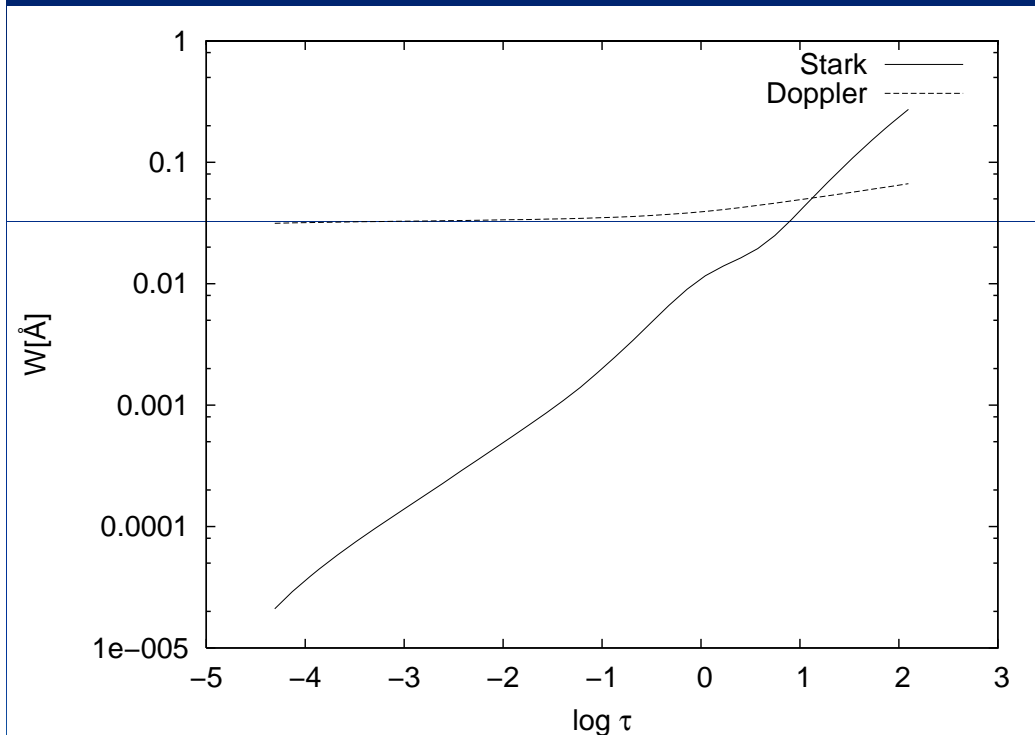
- **INVESTIGATION OF THE INFLUENCE OF STARK BROADENING ON PROFILES OF STELLAR SPECTRAL LINES**
- **STARK BROADENING AND MODELLING, ANALYZIS AND SYNTHEZIS OF STELLAR SPECTRA**
- **SPECTROSCOPICALLY DETECTABLE INFLUENCES OF COLLISIONAL PROCESSES ON ELECTRON DENSITY IN STELLAR ATMOSPHERES**

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 $T_e=9500\text{K}$ and $\log g=4.5$. The abundances of europium are a) $\log(\text{Eu}/\text{H})=-5.9$ and b) $\log(\text{Eu}/\text{H})=-7.5$



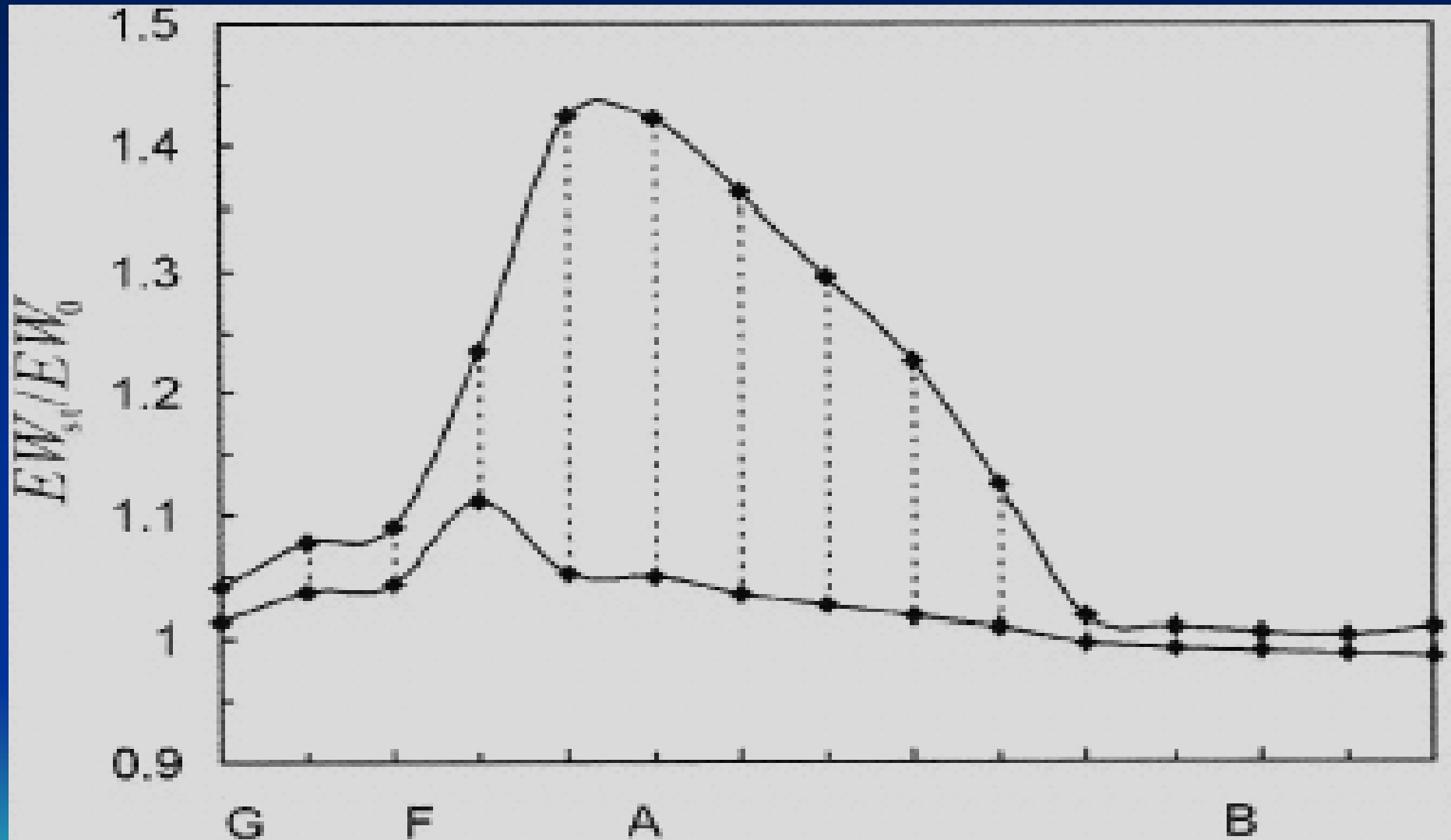
- **Astron. Astrophys.** 350, 719–724 (1999)
- *The electron-impact broadening effect in CP stars: the case of La II, La III, Eu II, and Eu III lines*
- L. C. Popovic, M.S. Dimitrijevic, and T. Ryabchikova

**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**
- **($T_{\text{eff}} = 10000$ 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 EW_{St}/EW₀ and minimum value for all 38 Nd II lines considered are summarized.

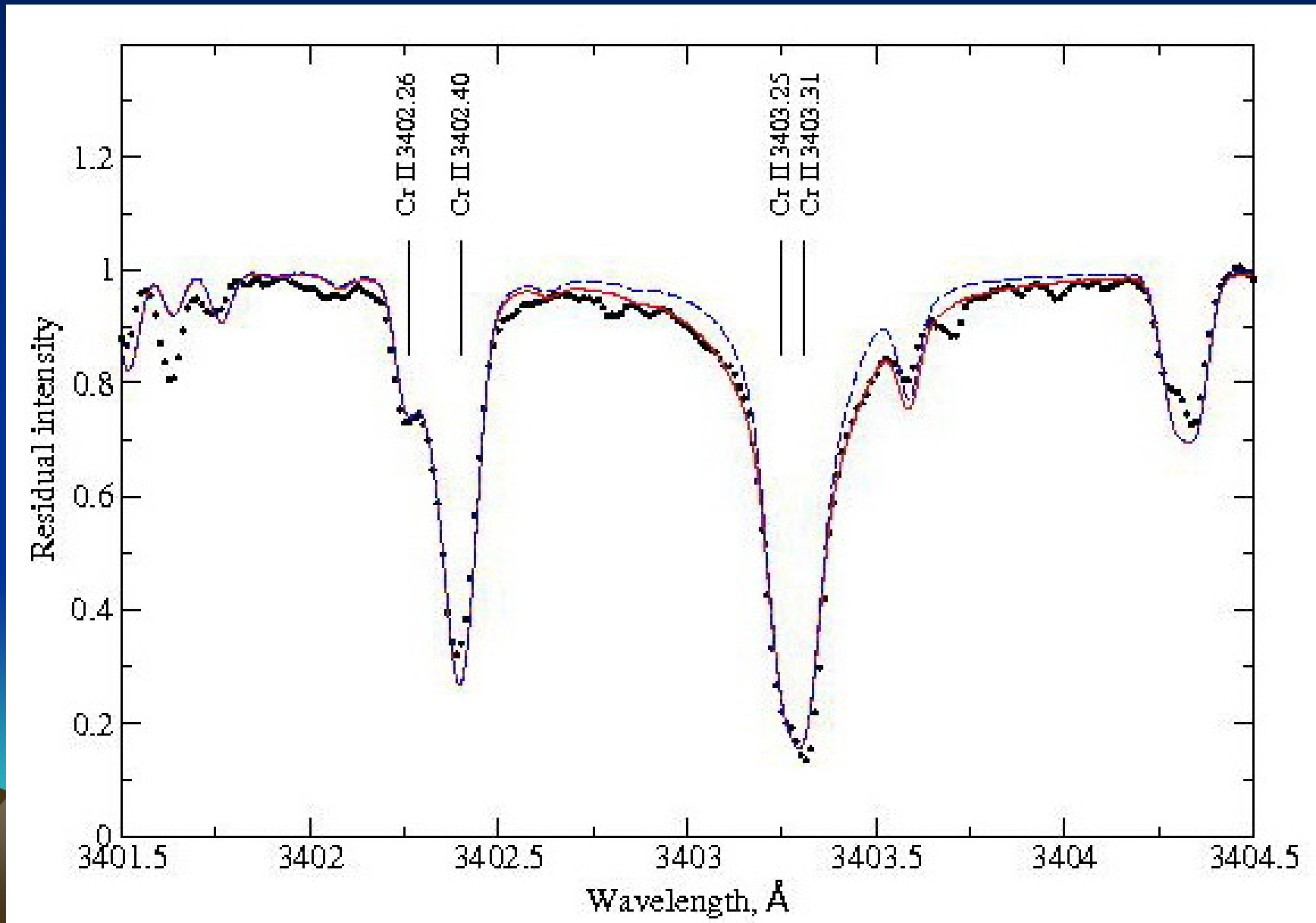


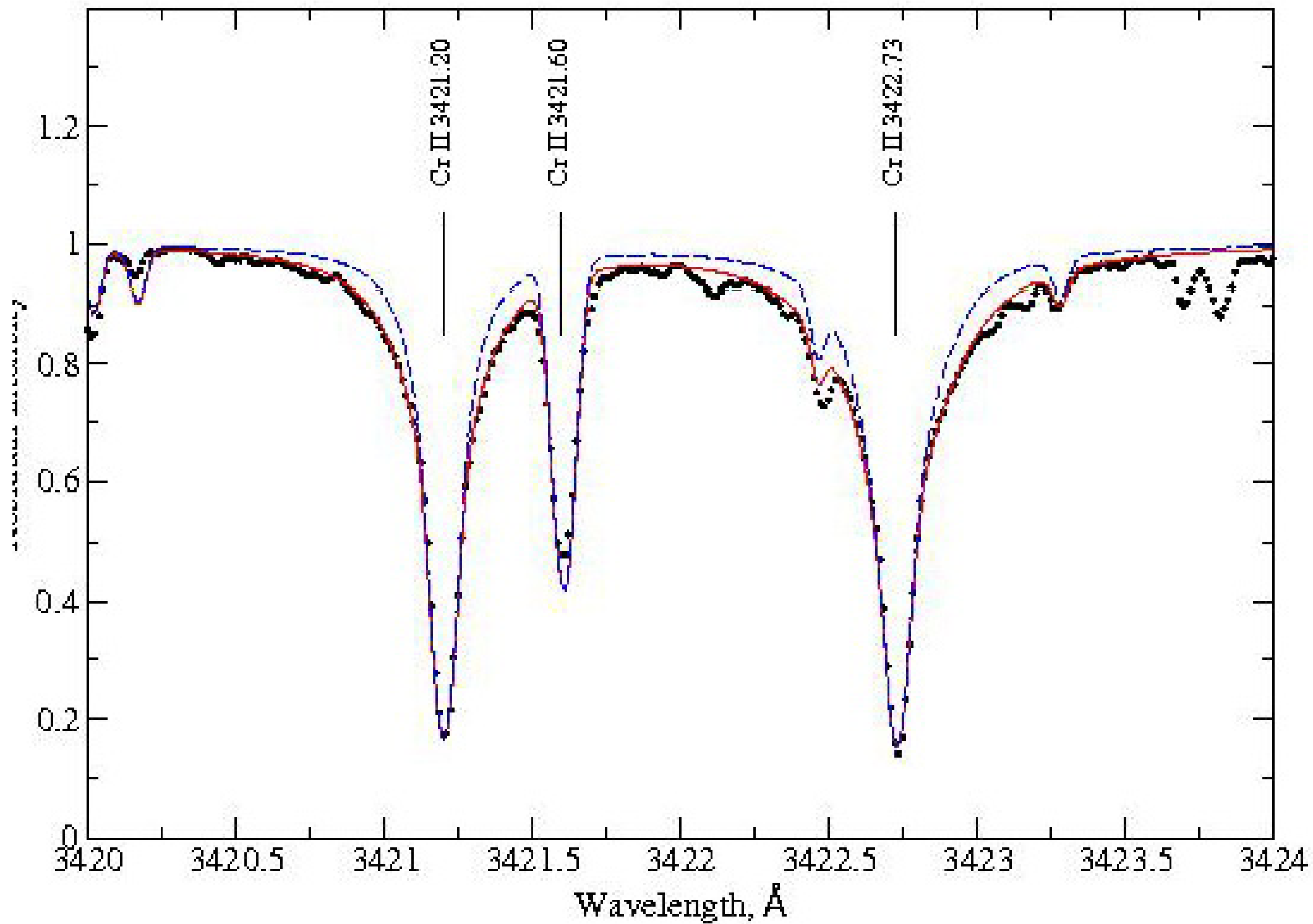
- THE ASTROPHYSICAL JOURNAL SUPPLEMENT SERIES, 135:109-114, 2001
- *STARK BROADENING EFFECT IN STELLAR ATMOSPHERES: Nd II LINES*
- L. C. POPOVIC , S. SIMIC,
- N. MILOVANOVIC, M. S.DIMITRIJEVIC

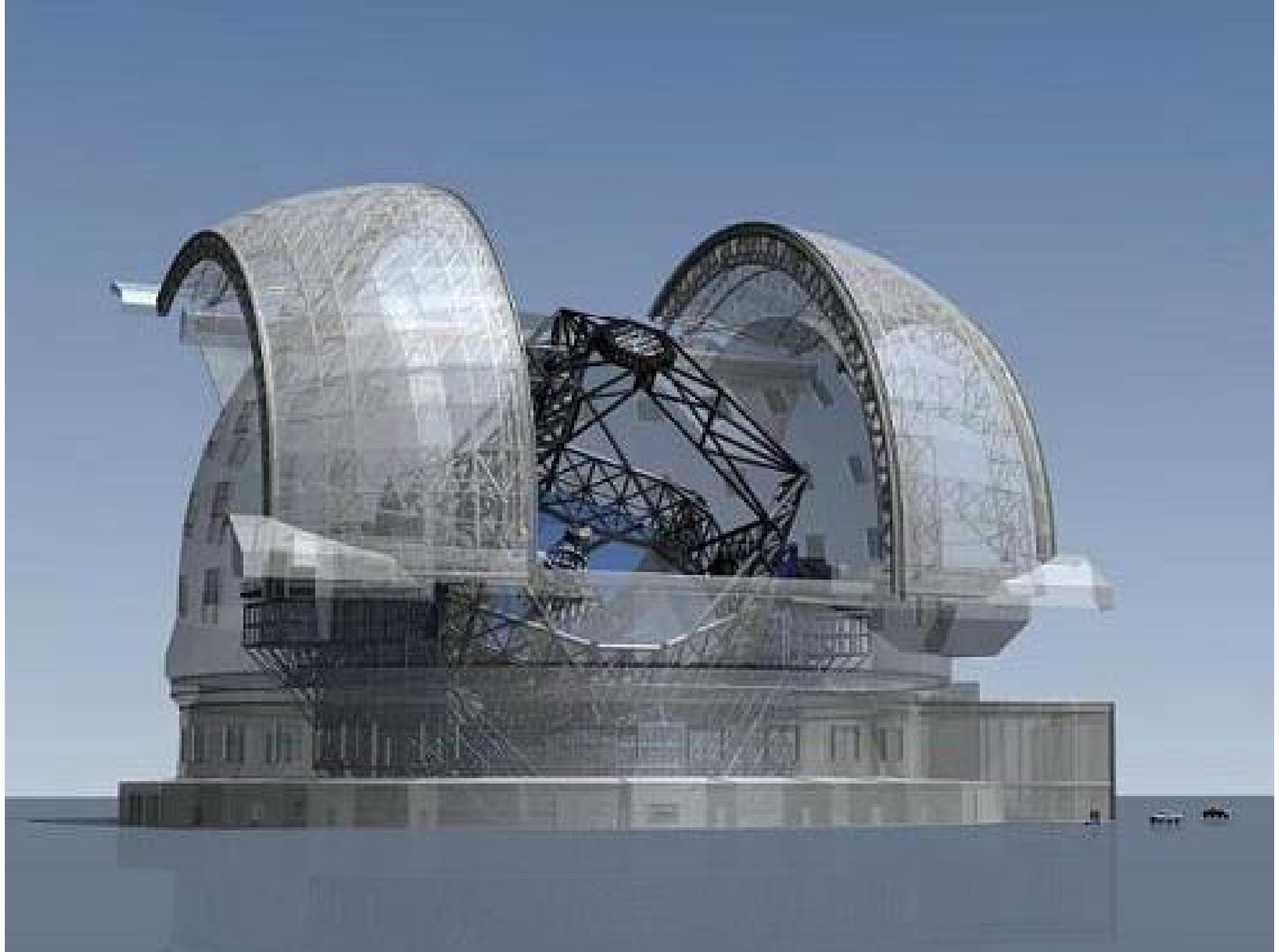
M. S. Dimitrijević, T. Ryabchikova, Z. Simić, L. Č. Popović and M. Dačić, *Astron. Astrophys.*, **469**, 681 (2007).

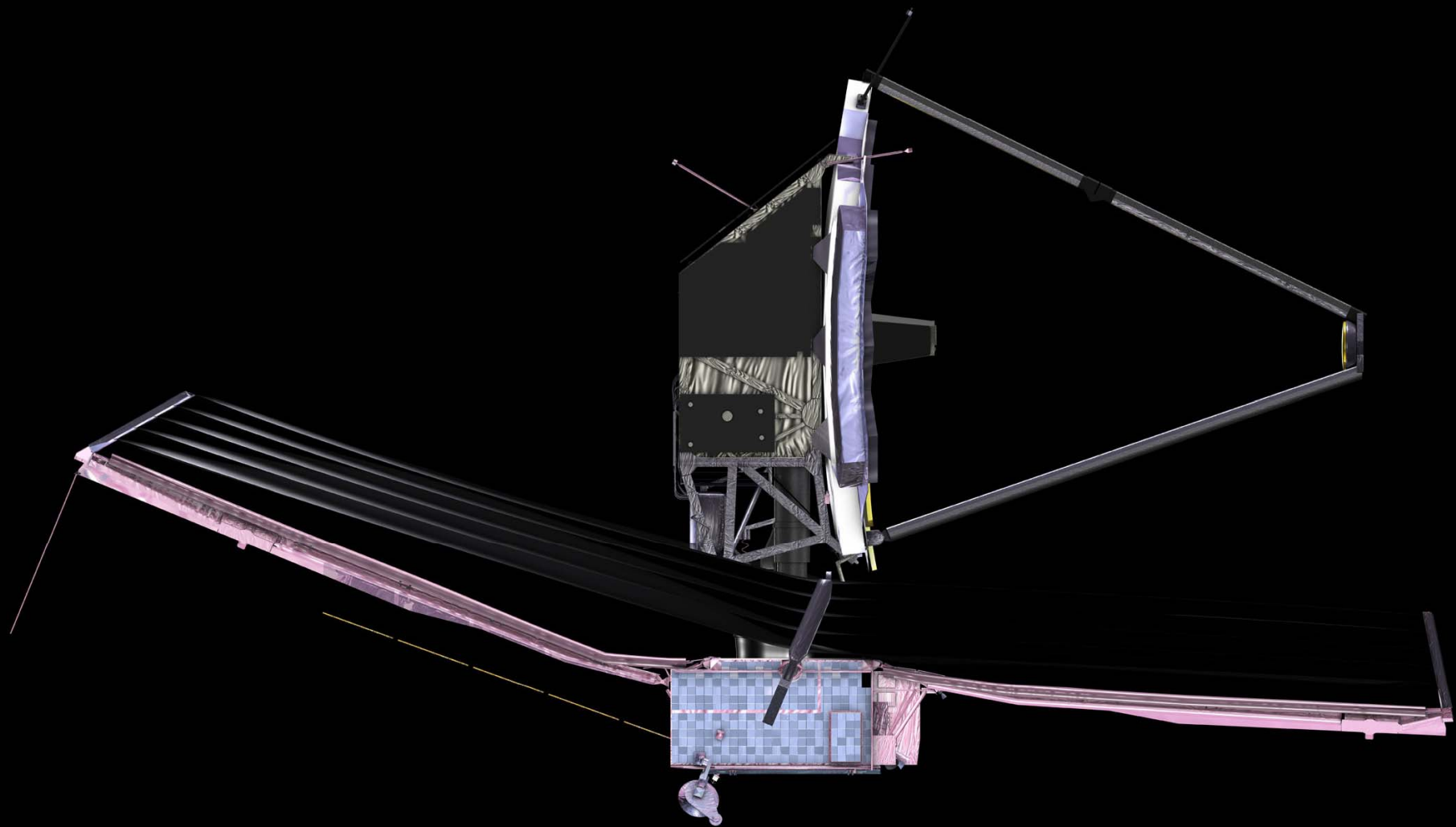
We investigated Stark broadening of Cr II lines in Ap star HD 133792 for which careful abundance and stratification analysis was performed by Kochukov et al. 2006, *A&A*, 460, 831. For this star $T_{\text{eff}}=9400$ K, $\log g = 3.7$. Code SYNTH3

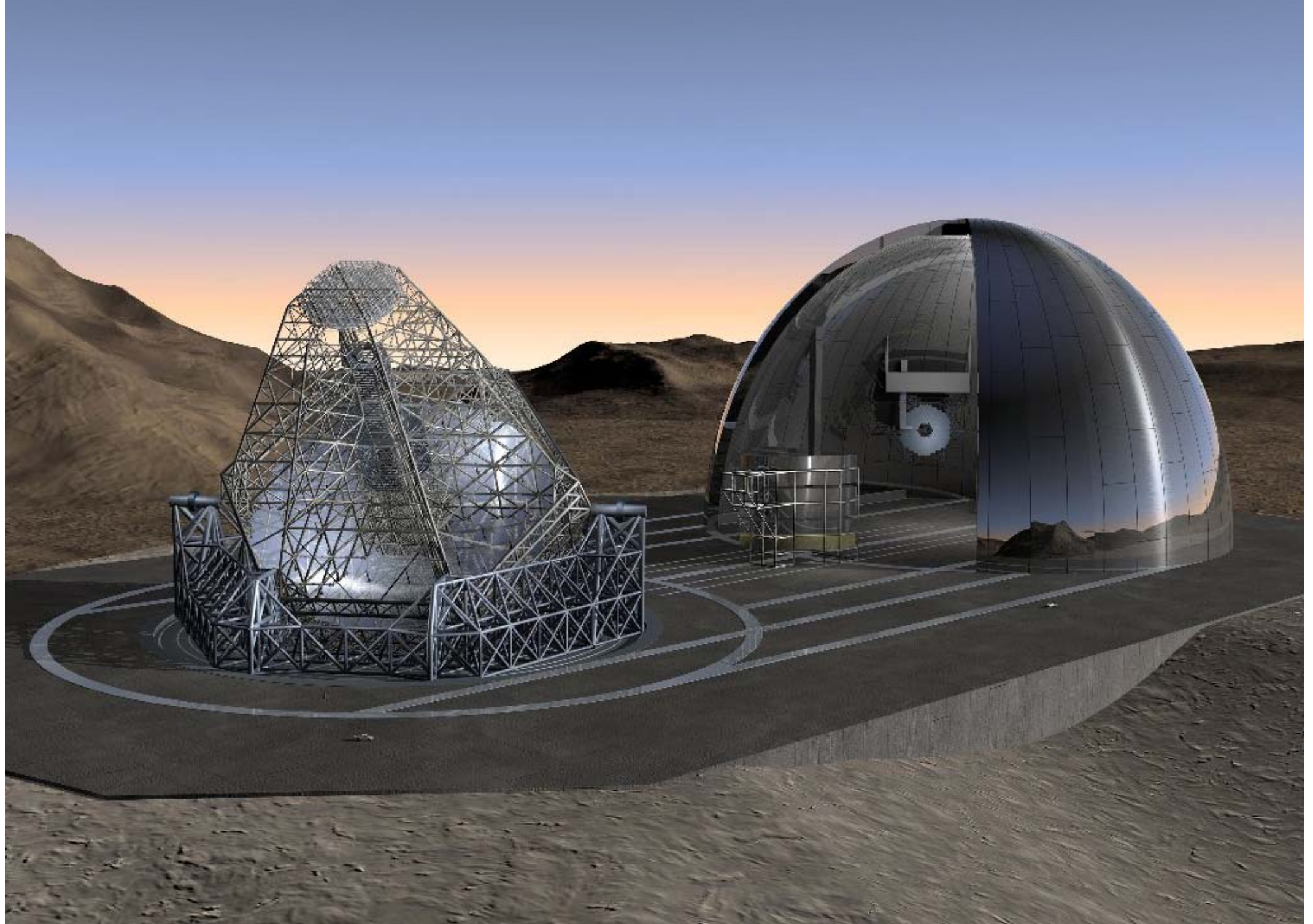
M. S. Dimitrijević, T. Ryabchikova, Z. Simić, L. Č. Popović and M. Dačić, *Astron. Astrophys.*, **469**, 681 (2007).





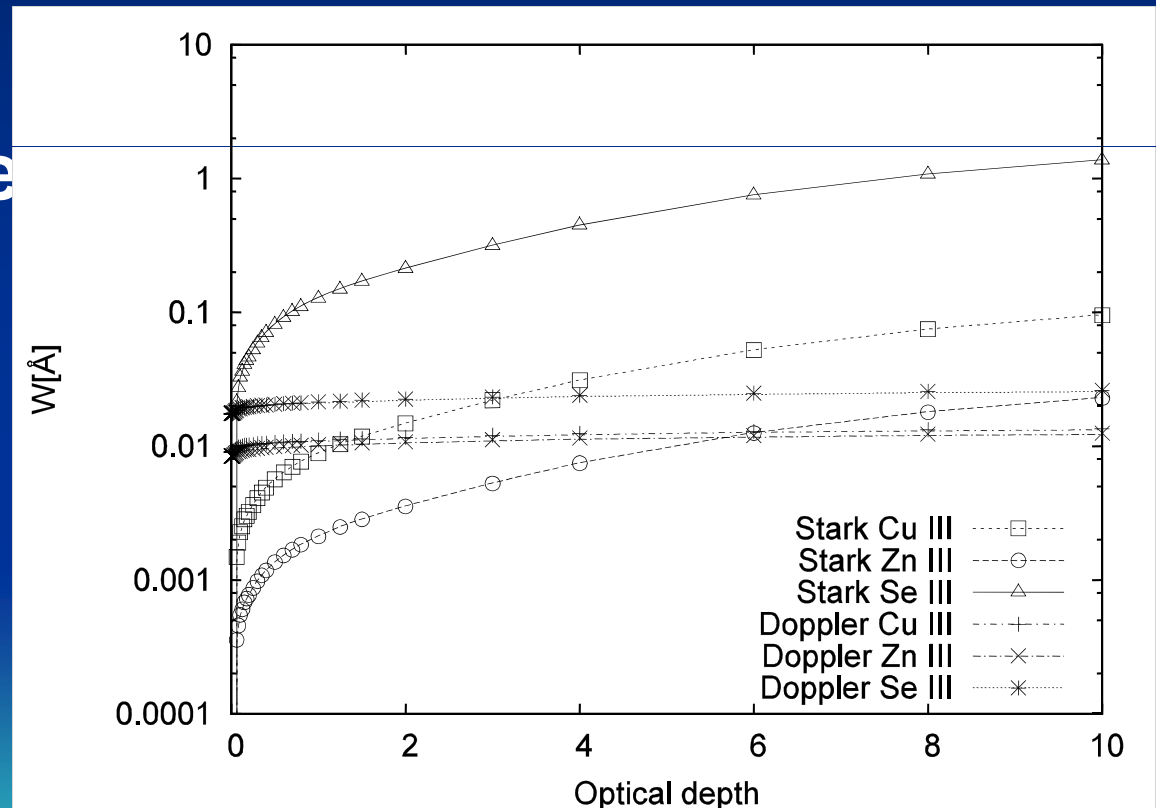






Z. Simić, M. S. Dimitrijević, L. Č. Popović
and M. Dačić, *New Astronomy*, 12, 187
(2006).

- Cu III 4s 2F - 4p 2 G° ($\lambda=1774.4 \text{ \AA}$), Zn III 4s 3D - 4p 3P° ($\lambda=1667.9 \text{ \AA}$) and Se III 4p5s 3 P° - 5p 3D ($\lambda=3815.5 \text{ \AA}$)
- DB WHITE DWARF
Teff = 15 000 K
- $\log g = 7$,



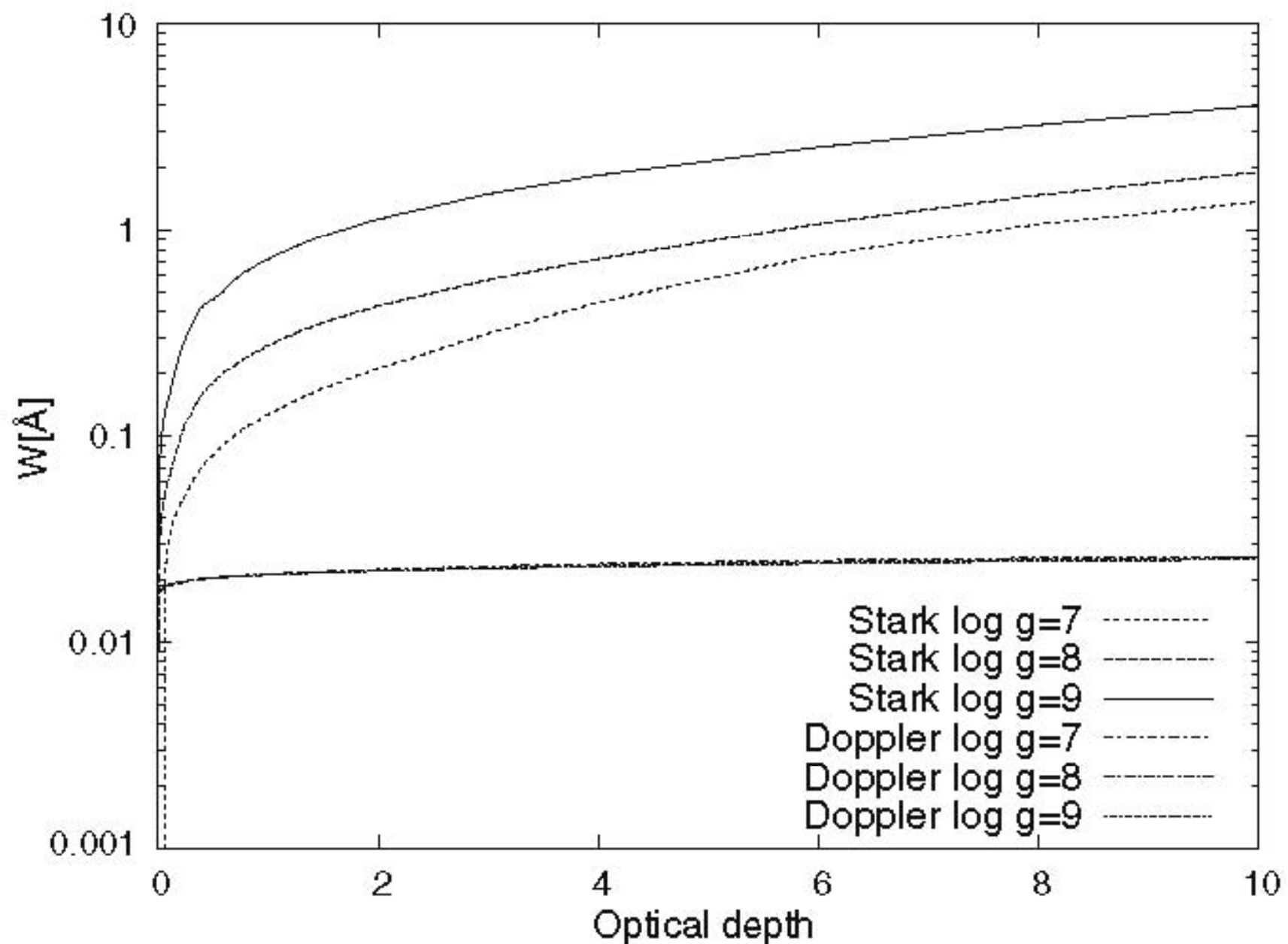


Fig. 4. Thermal Doppler and Stark widths for Se III spectral line $5s\ ^3P^0-5p\ ^3D$ ($\lambda = 3815.5\ \text{\AA}$) for a DB white dwarf atmosphere model with $T_{\text{eff}} = 150,00\ \text{K}$ and $7 \leq \log g \leq 9$, as a function of optical depth τ_{5150} .

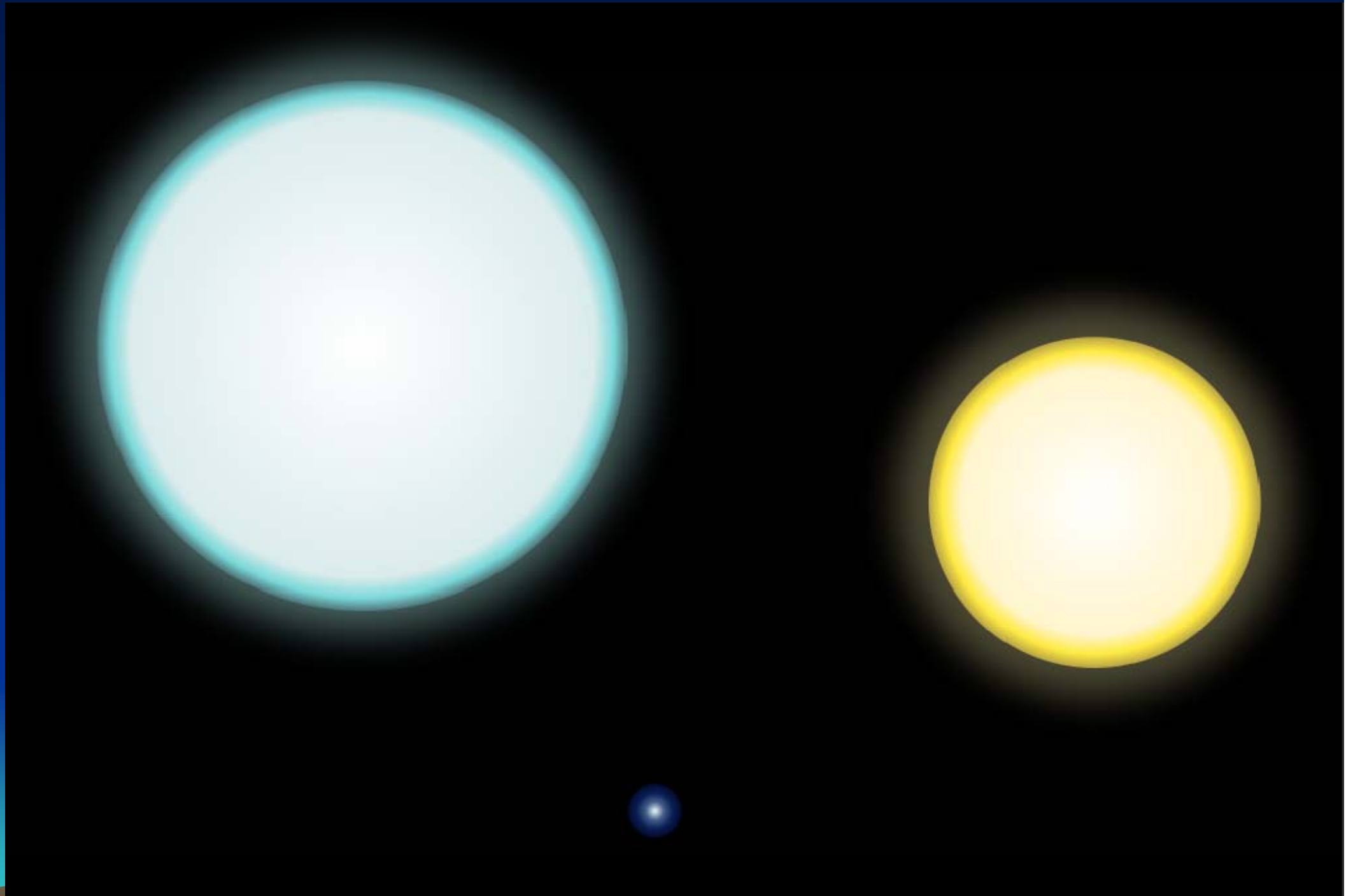
White dwarfs

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 $40\,000\text{ K} < T_{\text{eff}} < 100\,000\text{ K}$ He II

DB $12\,000\text{ K} < T_{\text{eff}} < 40\,000\text{ K}$ He I

DQ $4\,000\text{ K} < T_{\text{eff}} < 12\,000\text{ K}$ C, C₂ Swan
band

DZ lines of metals, accretion, DAZ, DBZ

DC continuum



- 1979 was discovered prototype of a new class of hot hydrogen deficient 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



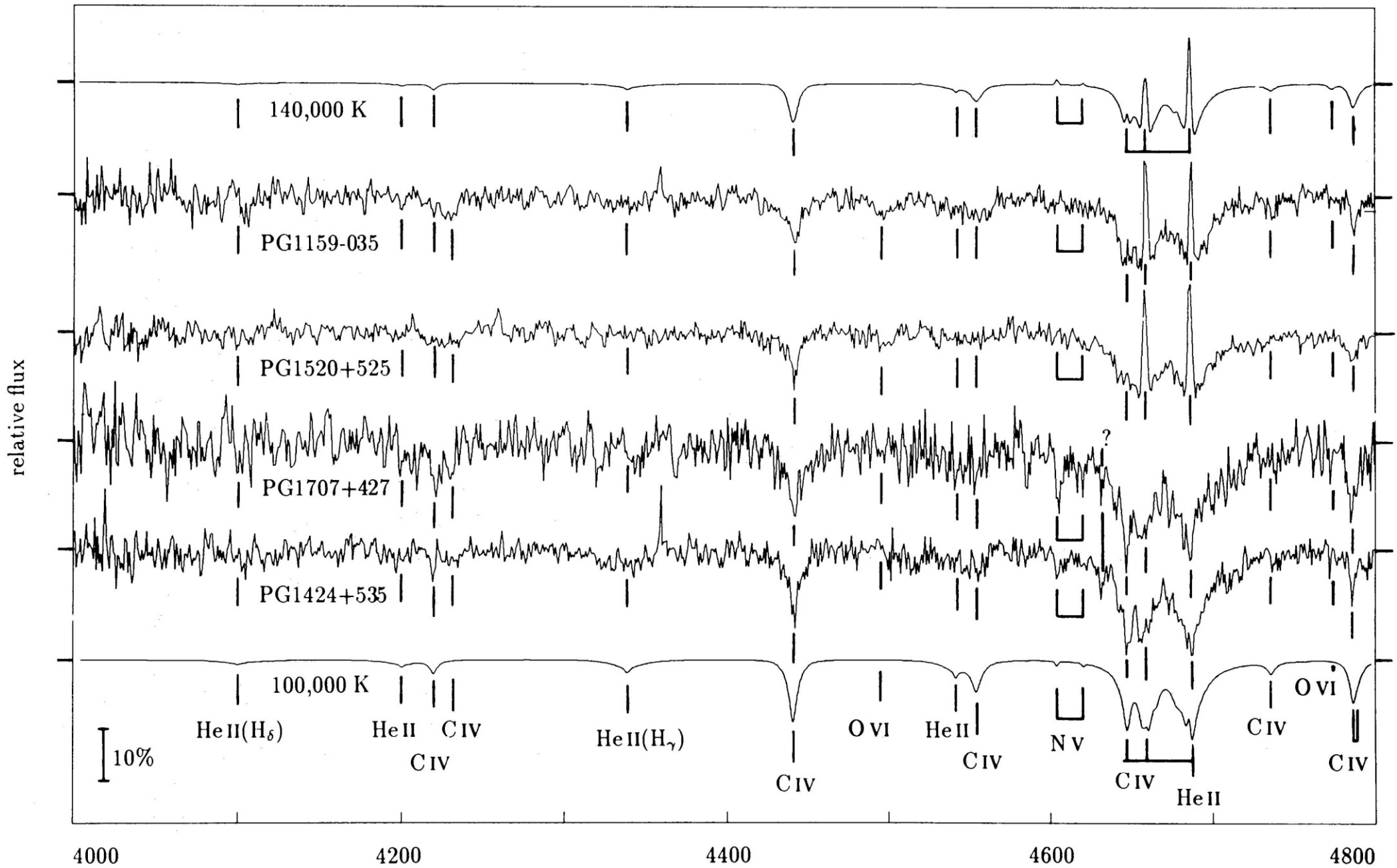


Table 3. Line identification list for the programme stars. These lines were identified in all stars if not indicated otherwise (labels: a=PG1159-035, b=PG1520+525, c=PG1424+535, d=PG1707+427). Doubtful identifications are marked by colons. Predicted line positions arising from some ions of interest which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

wave-length	ion	transition	wave-length	ion	transition
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
4492.7 ^{ab}	O VI	8-10	(4510.8)	N V	7f-9

- 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 deficient but also helium deficient. Atmosphere is composed from carbon and oxygen by equal amount.
- T_{eff} is $170000 \text{ K} \pm 20000 \text{ K}$ 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 Å. 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 – Asymptotic Giant Branch stars. Often this refers 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)



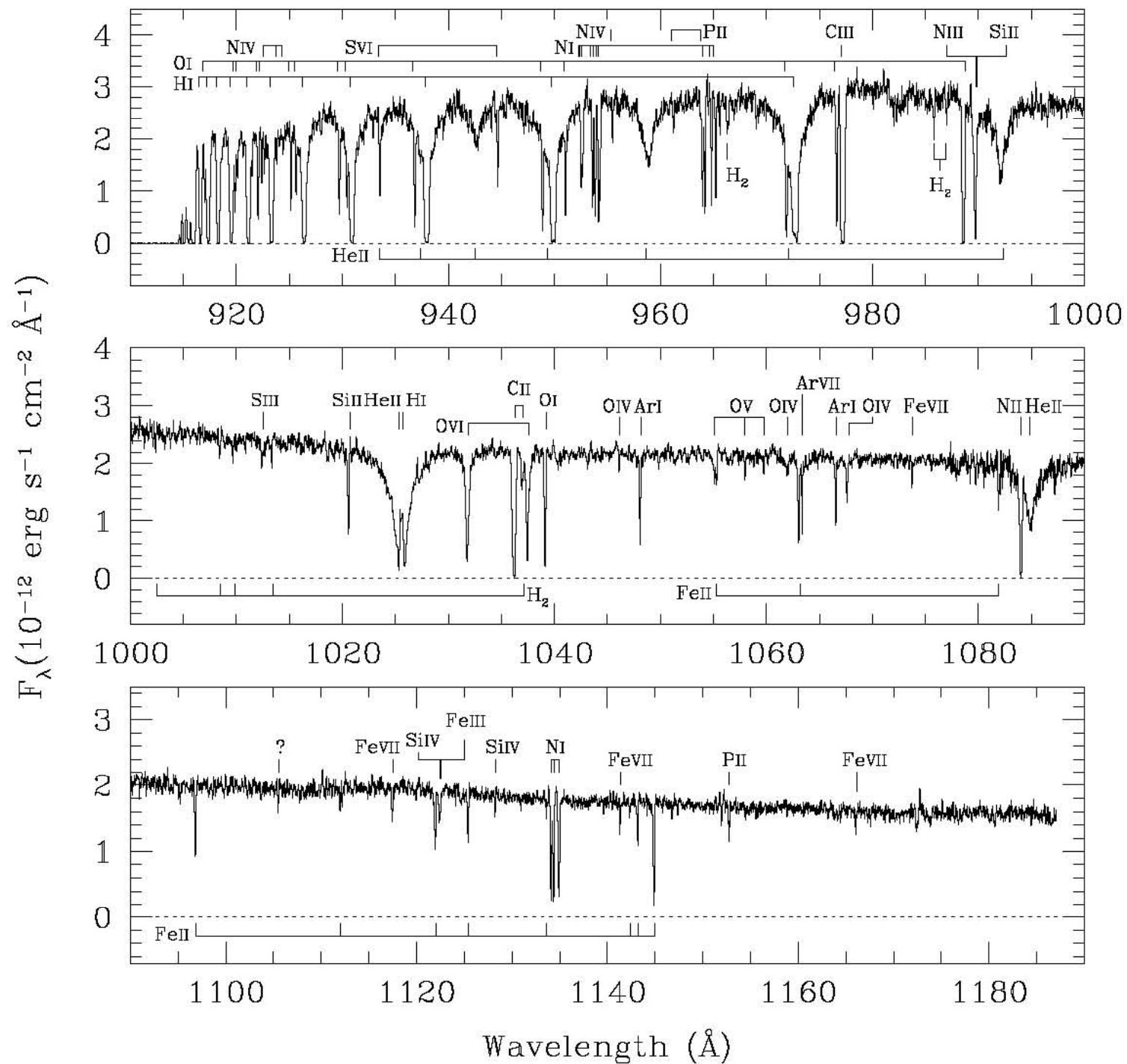


FIG. 1.—*FUSE* spectrum of GD 605. The main features present in the spectrum are labeled. This spectrum was obtained by merging the SiC1B, LiF1A, SiC2B, LiF2A, and LiF1B segments.

In Rauch et al. 2007, A&A, 470, 317 was pointed out that line broadening data for 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
- $\sigma_{ij}(\Delta\lambda) = (\pi e^2 / mc^2) \lambda^2 (f_{ij} / s_n F_0) U(\Delta\lambda / s_n F_0)$
- 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
- $F_0 = 2.61 e (\sum Z_{ion}^{3/2} n_{ion})^{2/3}$



- Here $Z_{\text{ion}}, n_{\text{ion}}$ 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).

17

- Si VI 2p⁴(3P)3s 2P-2p⁴(3P)3p 2 D° ($\lambda = 1226, 7\text{\AA}$)
- DO WHITE DWARFS
T_{eff} = 50 000–100 000 K and log g = 8.

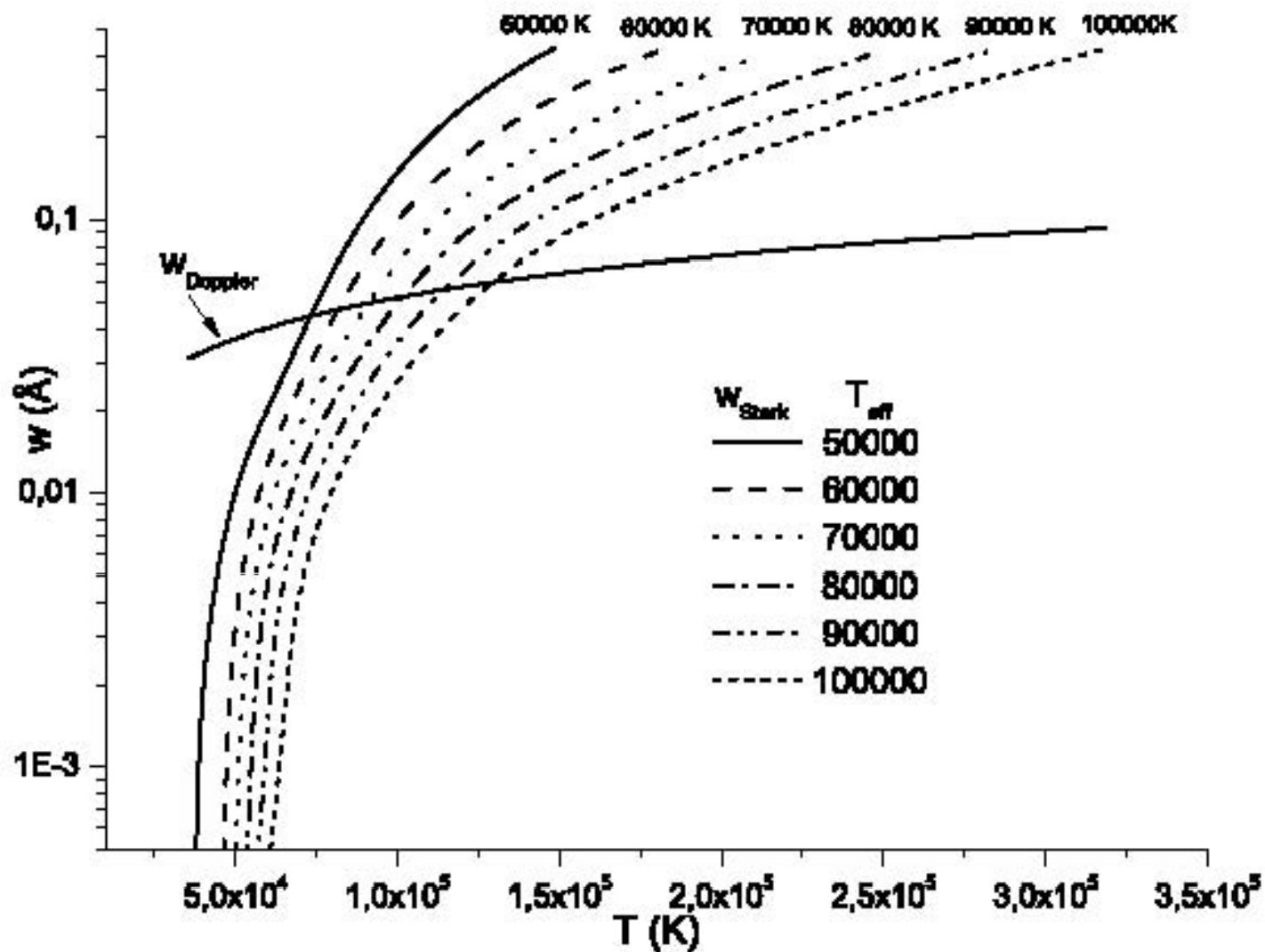


Figure 1. Stark and Doppler widths for Si VI $2p^4(^3P)3s^2P-2p^4(^3P)3p^2D^0$ ($\lambda = 1226, 7 \text{ \AA}$) spectral line as a function of atmospheric layer temperatures. Stark widths are shown for six atmospheric models with effective temperature $T_{\text{eff}} = 50\,000\text{--}100\,000 \text{ K}$ and $\log g = 8$.

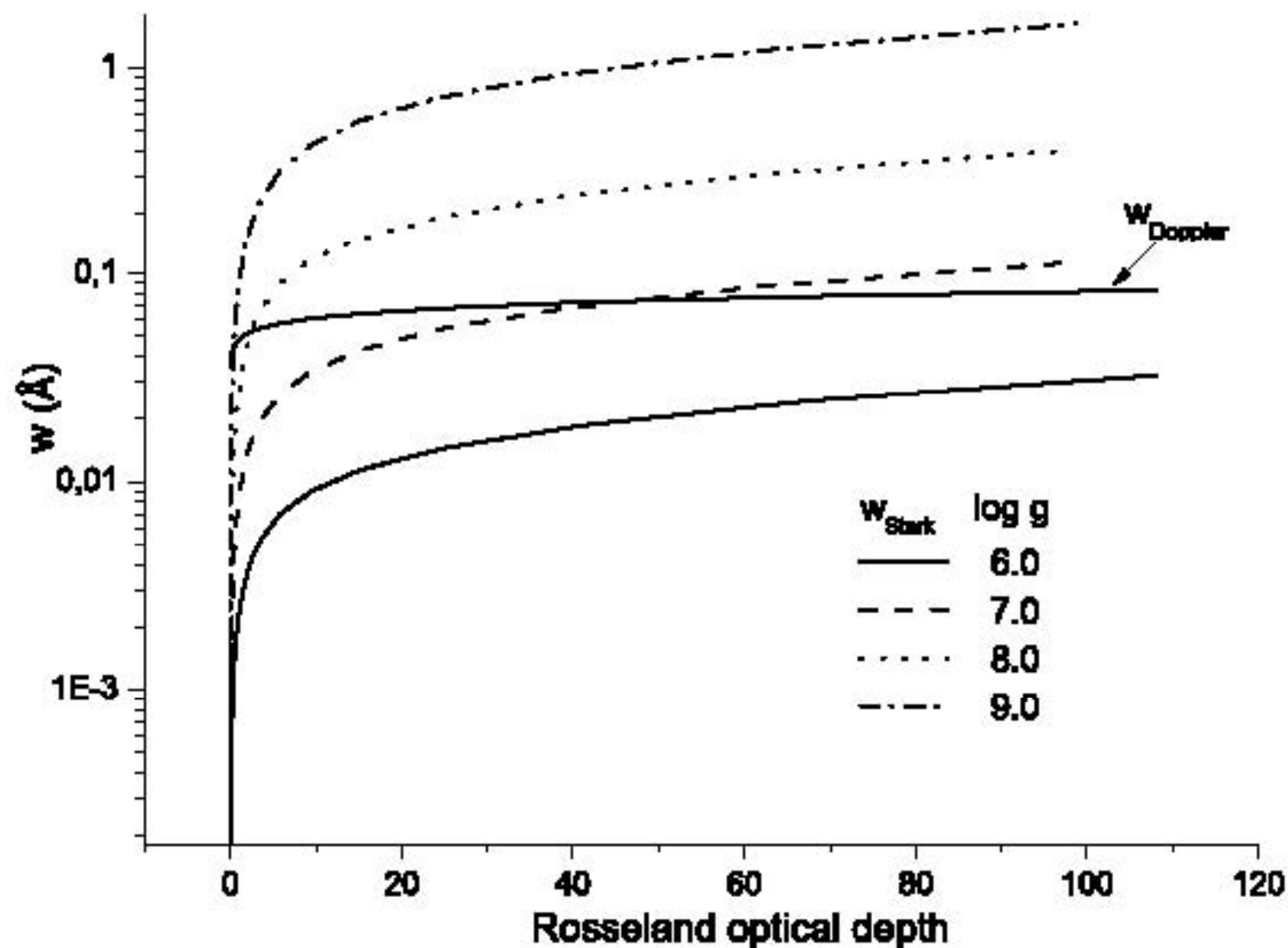


Figure 4. Stark and Doppler widths for Si VI $2p^4(^3P)3s^2P-2p^4(^3P)3p^2D^o$ ($\lambda = 1226, 7 \text{ \AA}$) spectral line as a function of Rosseland optical depth. Stark widths are shown for four values of model gravity $\log g = 6-9$, $T_{\text{eff}} = 80\,000 \text{ K}$.

- DQ $4\,000\text{ K} < T_{\text{eff}} < 12\,000\text{ K}$ C, C₂
Swan band
- Liebert et al. 2003 found DQ with C II lines ($T_{\text{eff}} 12\,000 - 13\,000\text{ K}$)
- Dufour et al investigate in SDSS and find hot DQ stars with $T_{\text{eff}} 18\,000 - 24\,000\text{ K}$ without lines of H and He and mostly with C II lines.

LETTERS

White dwarf stars with carbon atmospheres

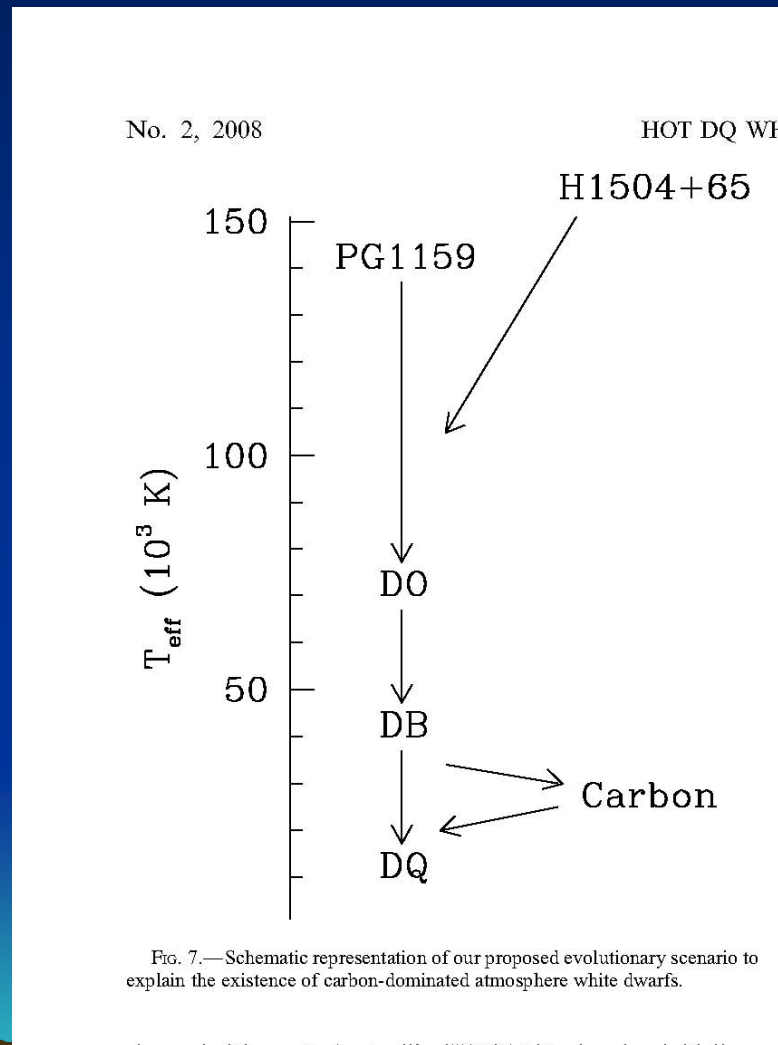
P. Dufour¹, J. Liebert¹, G. Fontaine² & N. Behara³

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

with H1504+65, might be the result of a different evolutionary path that these stars had thinner outer helium envelopes so that they occurred earlier in the cooling sequence. These highly polluted white dwarfs are expected to be massive, so it is possible that they might represent the missing high-mass tail of the white dwarf distribution¹⁴.

Thus, it is with this scientific rationale in mind that we have proceeded with the calculation of the appropriate atmospheric models for these objects. Because the continuum opacity of heavy elements is expected to be negligible for these objects, these new models have been developed with the latest C and O photoionization cross-sections from the Opacity Project¹⁵. Although the analysis of the cooling curves ($T_{\text{eff}} < 15,000$ K) is straightforward (results will be published elsewhere; manuscript in preparation), we quickly realized that a combination of carbon and helium could successfully reproduce the observed features (mostly C II lines) in the optical spectra of the hottest ones by assuming a helium-dominated atmosphere. However, such models predict the presence of a strong He I $\lambda = 4,481$ Å line, not observed spectroscopically in our sample of hot I D stars. We conclude that the observed features in the spectra of these stars

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



- 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

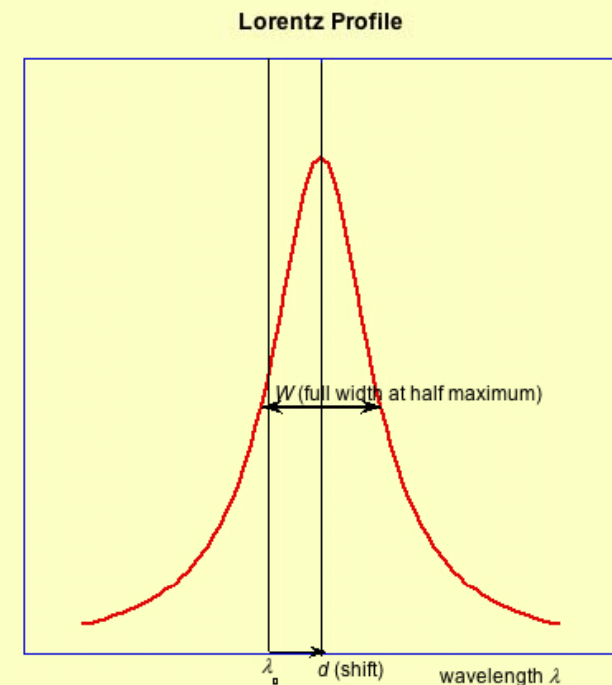
S. Sahal-Bréchet*, M.S. Dimitrijević** (scientists responsible of Stark-b)
and N. Moreau* (Research engineer)

*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-Bréchet (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-Bréchet
- **Accuracy** : about 20%, sometimes better, sometimes less
- **More than 1500 citations (ADS)** for the whole work



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

STARK-B

- <http://stark-b.obspm.fr/>

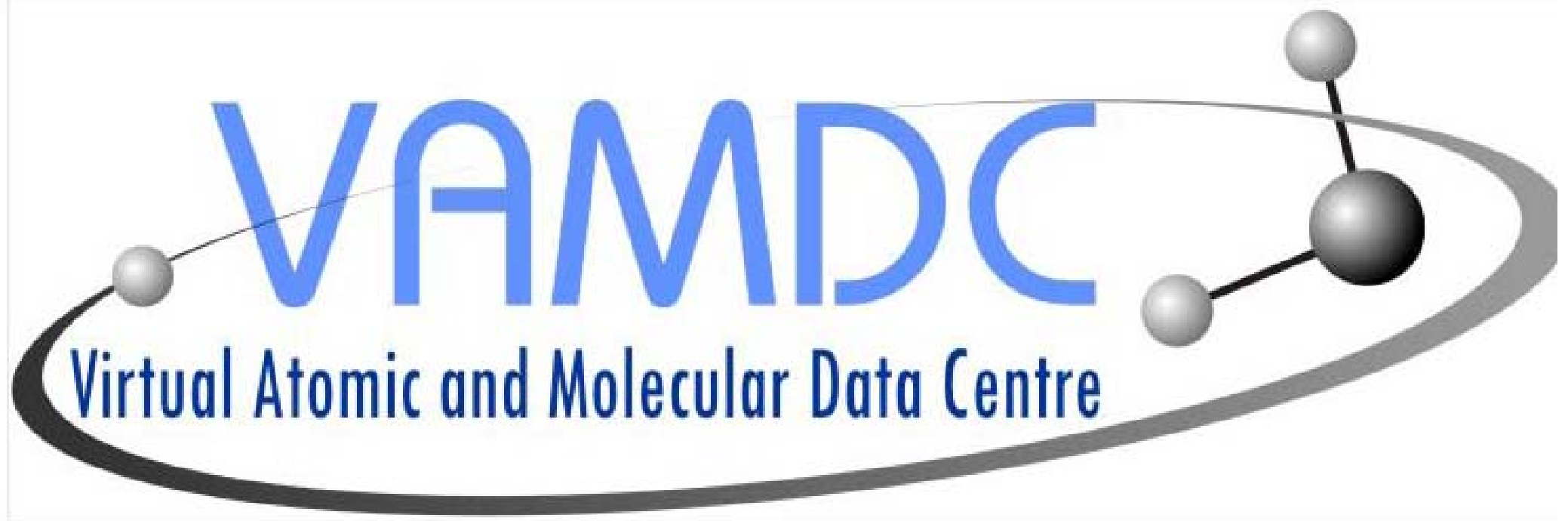
-

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

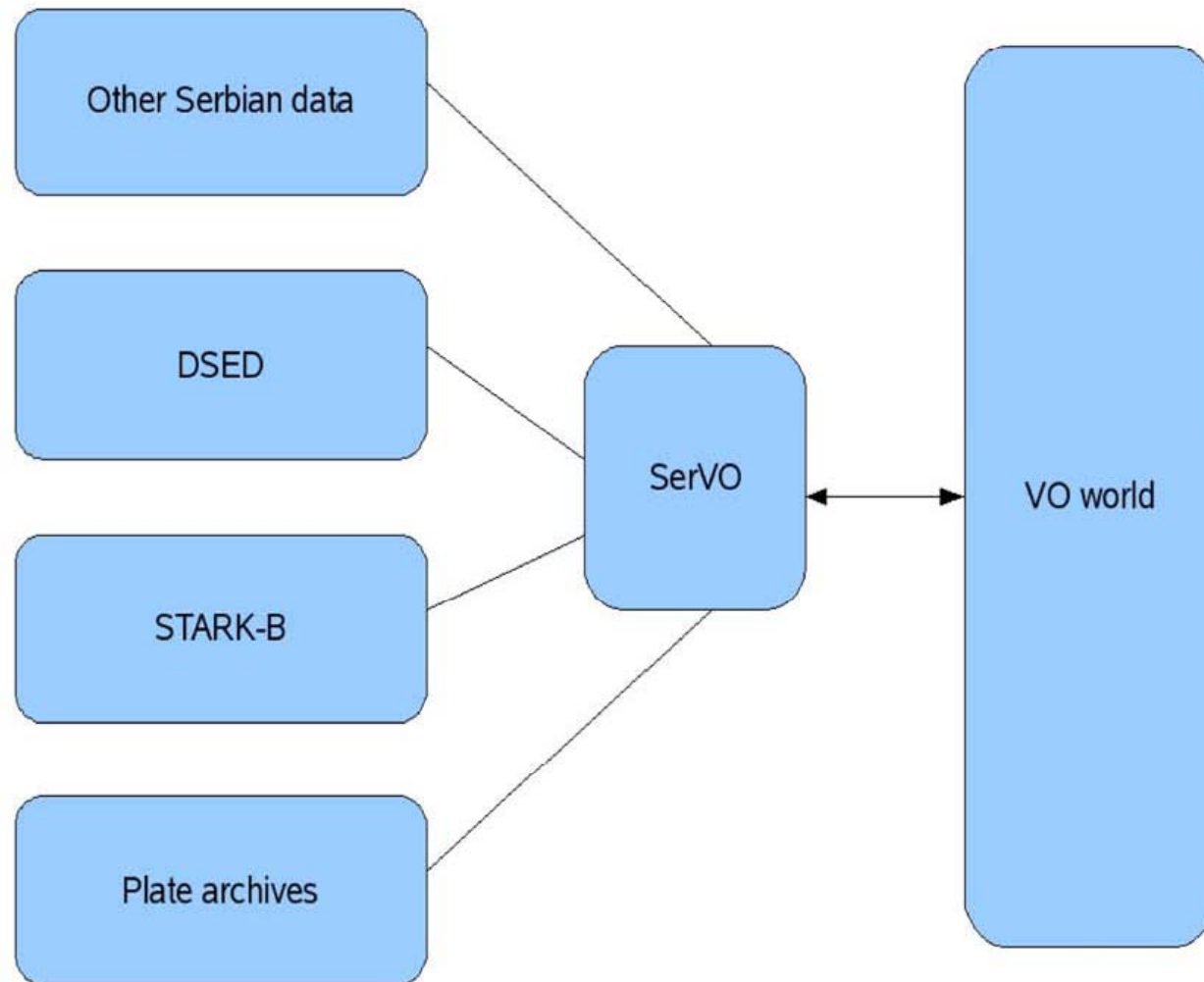
VAMDC

- 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

