1st workshop:

Astrophysical winds and disks
Similar phenomena in stars and quasars

STARK BROADENING OF SPECTRAL LINES OF INERT GASES

Magdalena Christova – Technical University-Sofia
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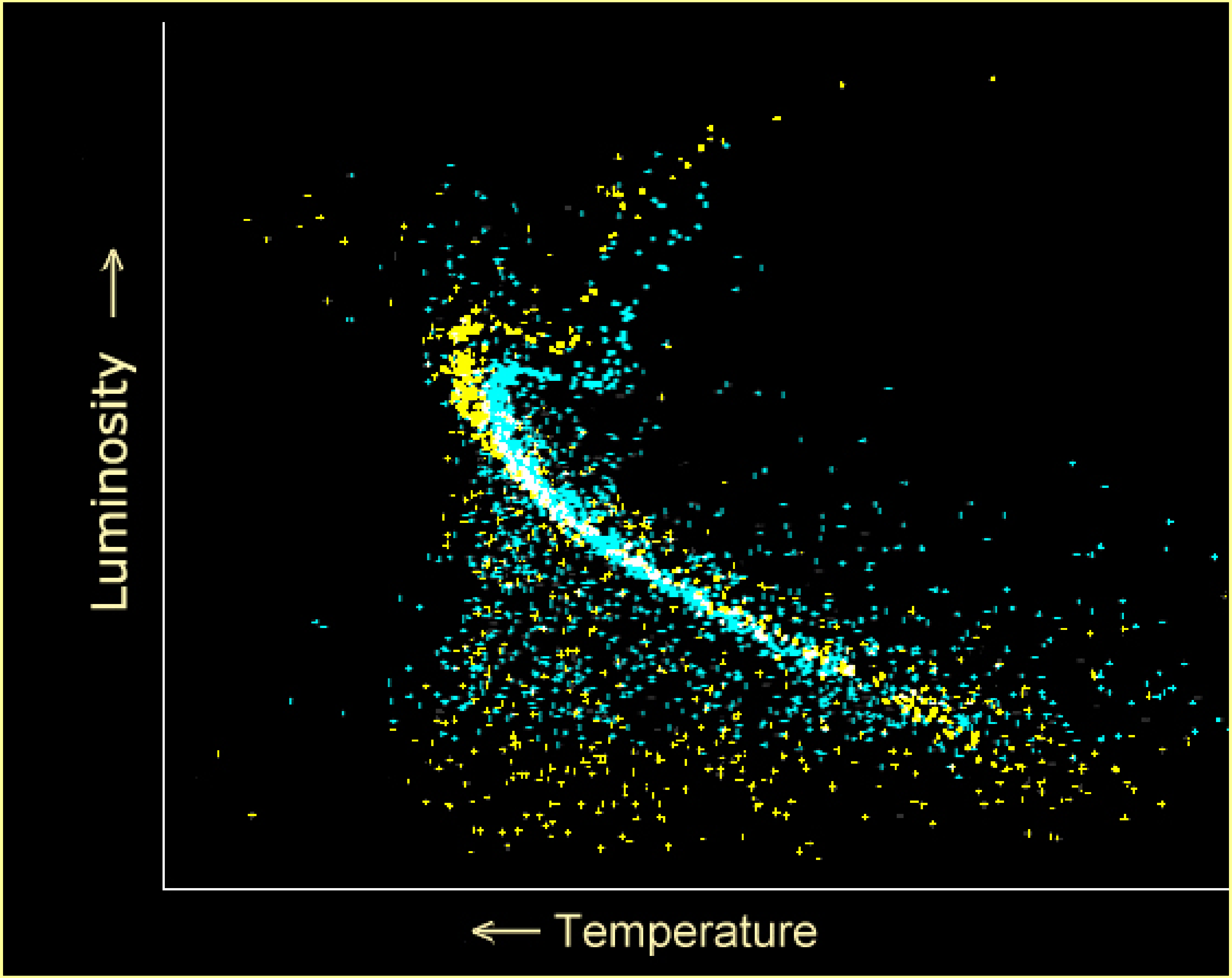
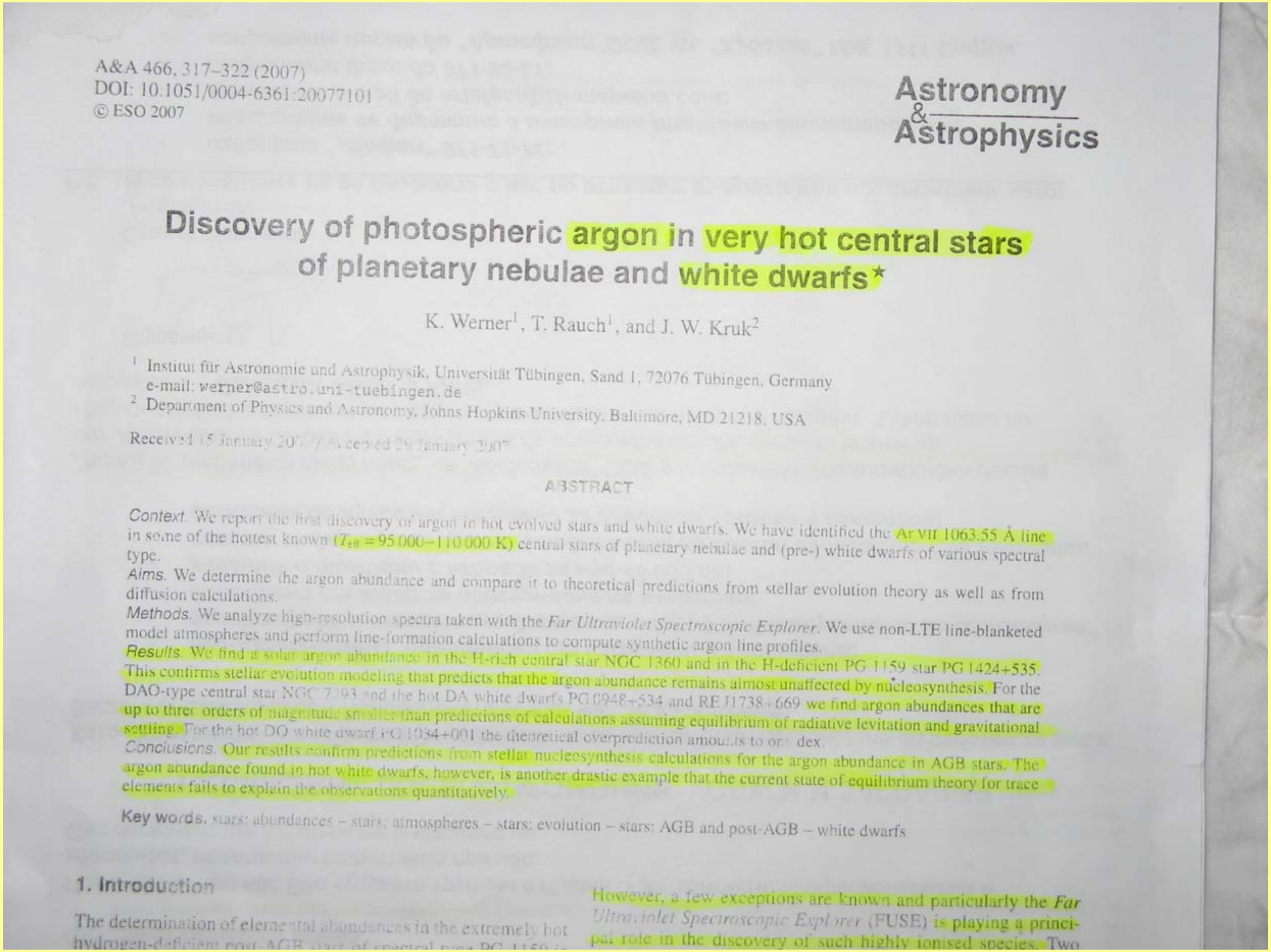
Platamonas 6 September 2009


Luminosity →
← Temperature

In the literature



A&A 466, 317–322 (2007)
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Astronomy & Astrophysics

Discovery of photospheric argon in very hot central stars of planetary nebulae and white dwarfs*

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ABSTRACT

Context. We report the first discovery of argon in hot evolved stars and white dwarfs. We have identified the Ar VII 1063.55 Å line in some of the hottest known (T_{eff} = 95 000–110 000 K) central stars of planetary nebulae and (pre-) white dwarfs of various spectral type.

Aims. We determine the argon abundance and compare it to theoretical predictions from stellar evolution theory as well as from diffusion calculations.

Methods. We analyze high-resolution spectra taken with the *Far Ultraviolet Spectroscopic Explorer*. We use non-LTE line-blanketed model atmospheres and perform line-formation calculations to compute synthetic argon line profiles.

Results. We find a solar argon abundance in the H-rich central star NGC 1360 and in the H-deficient PG 1159 star PG 1424+535. This confirms stellar evolution modeling that predicts that the argon abundance remains almost unaffected by nucleosynthesis. For the DAO-type central star NGC 7293 and the hot DA white dwarfs PG 0948+534 and RE J1738+669 we find argon abundances that are up to three orders of magnitude smaller than predictions of calculations assuming equilibrium of radiative levitation and gravitational settling. For the hot DO white dwarf PG 1034+001 the theoretical overprediction amounts to one dex.

Conclusions. Our results confirm predictions from stellar nucleosynthesis calculations for the argon abundance in AGB stars. The argon abundance found in hot white dwarfs, however, is another drastic example that the current state of equilibrium theory for trace elements fails to explain the observations quantitatively.

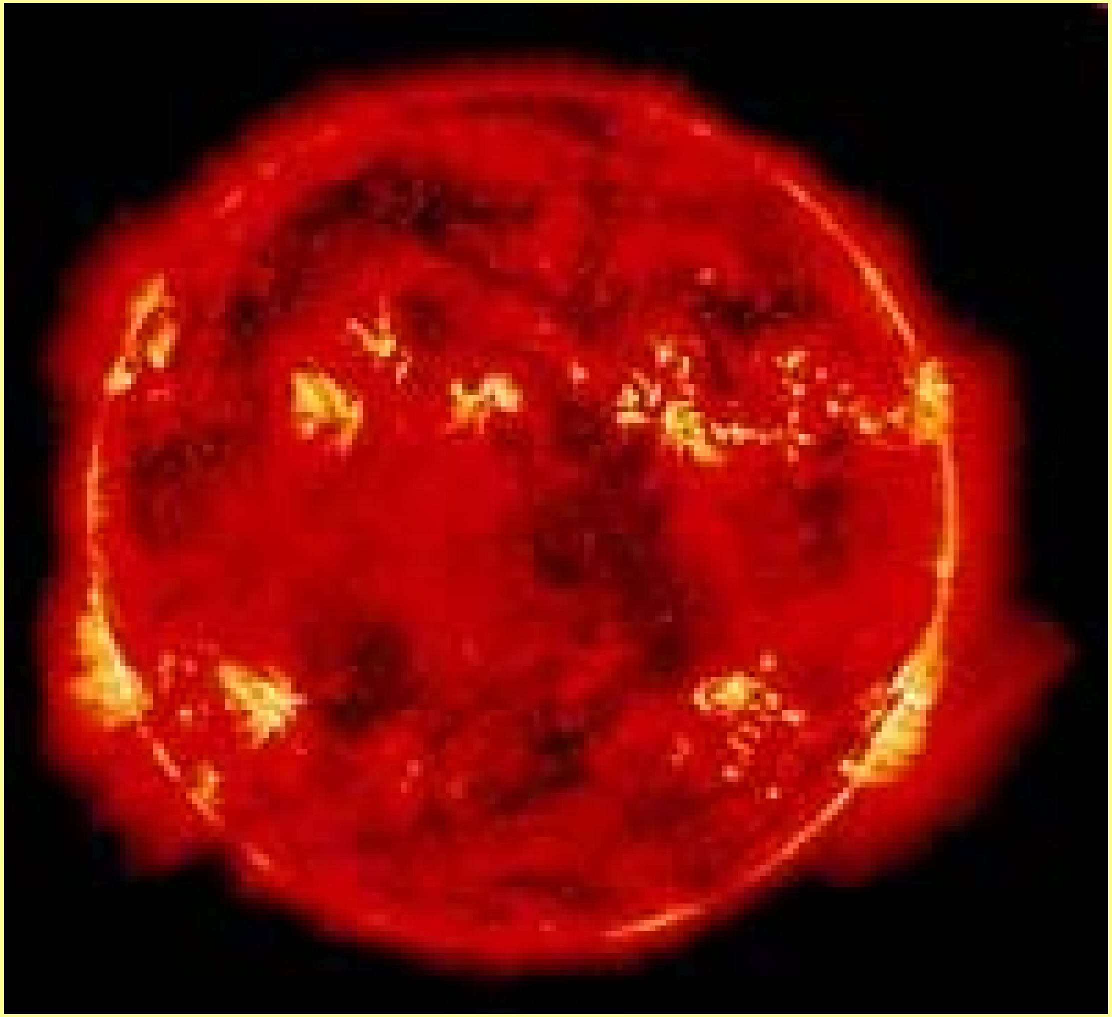
Key words. stars: abundances – stars: atmospheres – stars: evolution – stars: AGB and post-AGB – white dwarfs

1. Introduction

The determination of elemental abundances in the extremely hot hydrogen-deficient post-AGB stars of spectral type PG 1159 is

However, a few exceptions are known and particularly the *Far Ultraviolet Spectroscopic Explorer* (FUSE) is playing a principal role in the discovery of such highly ionised species. Two

Sun

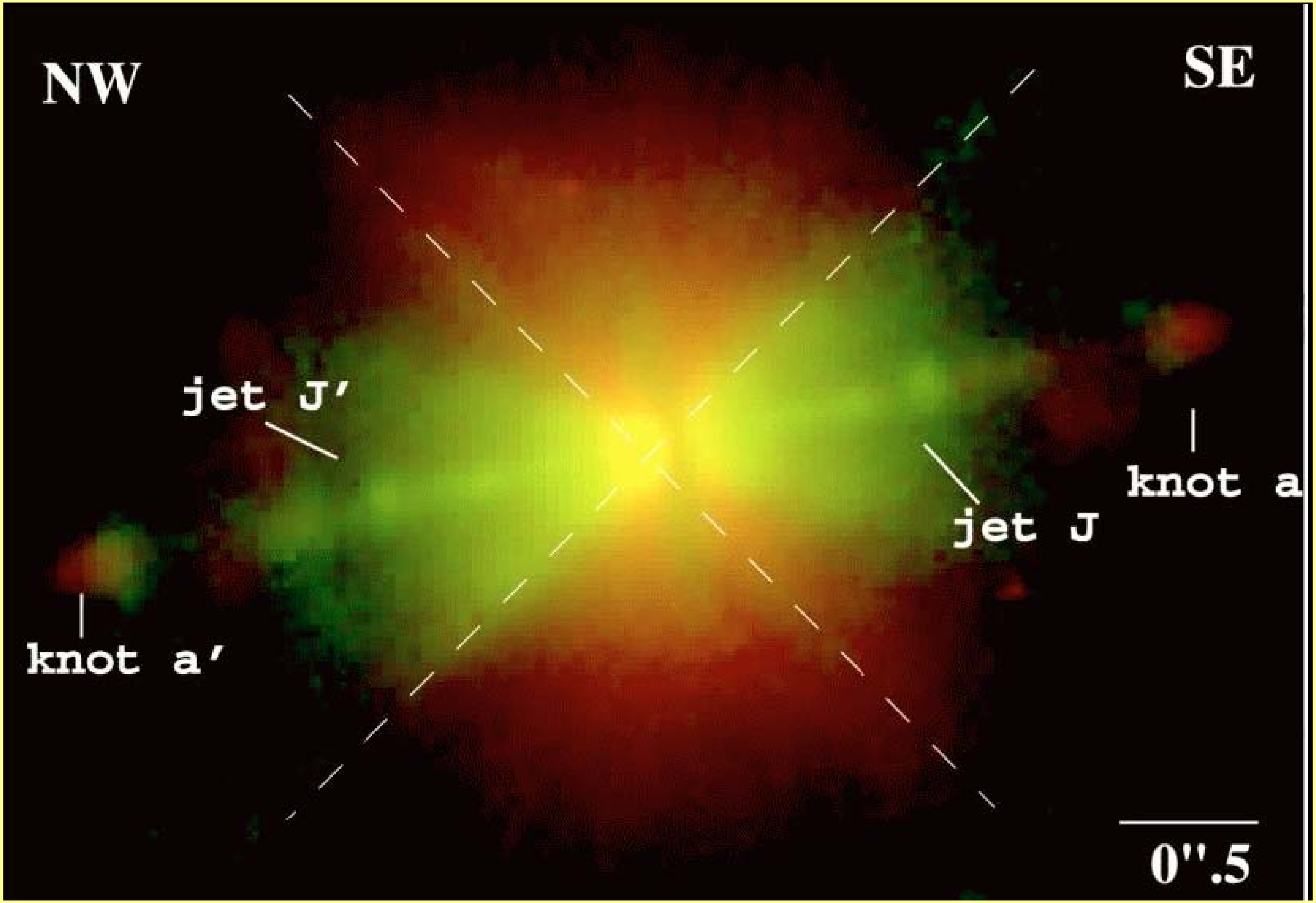


He; Ar

B[e]-star Hen 2-90

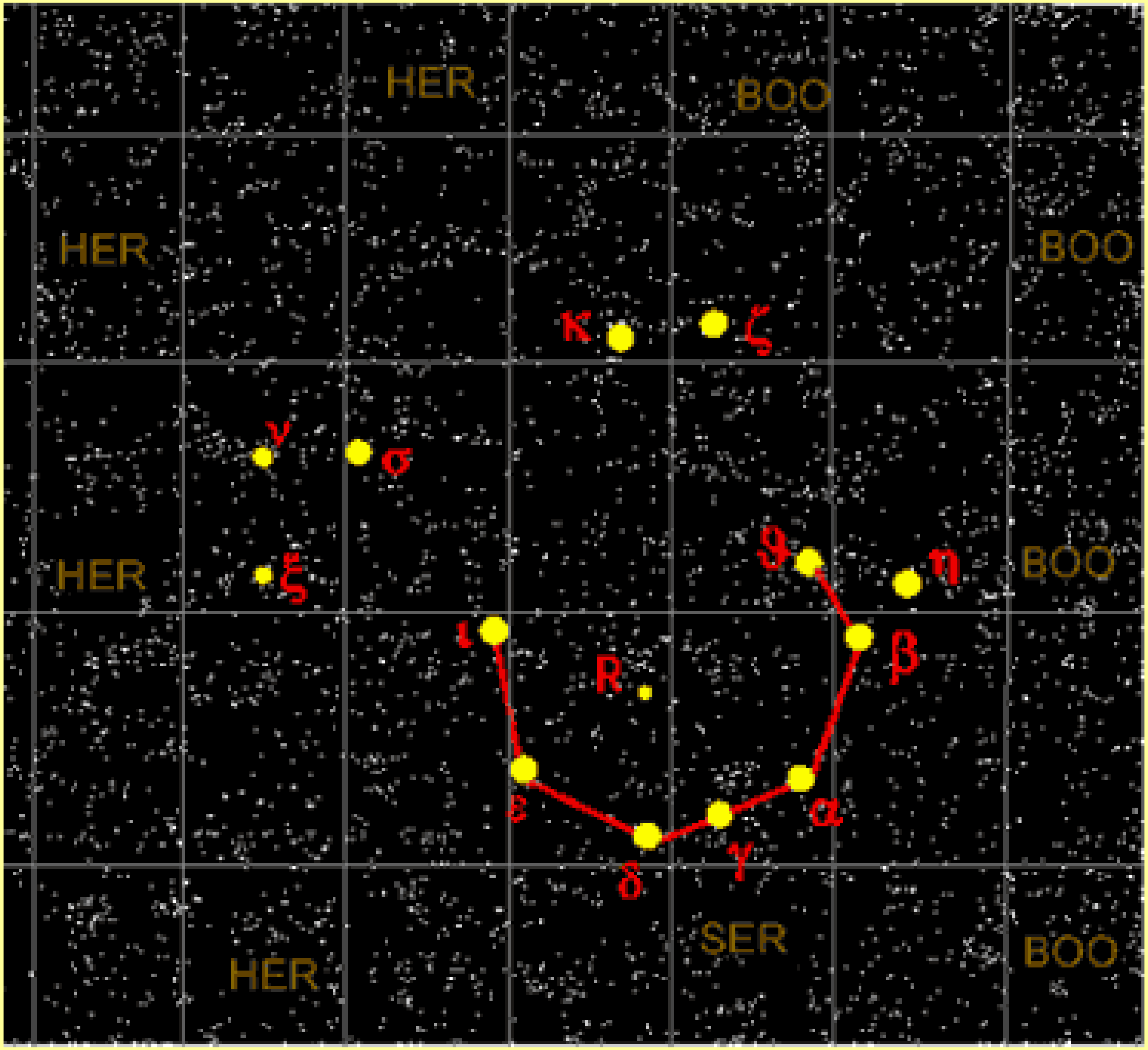
He I; Ar III

T = 51 000 K



Kraus M, Borges F M, De Araújo F X, Lamers H J G L M 2005 *Astron. Astrophys.* **441** 289-302

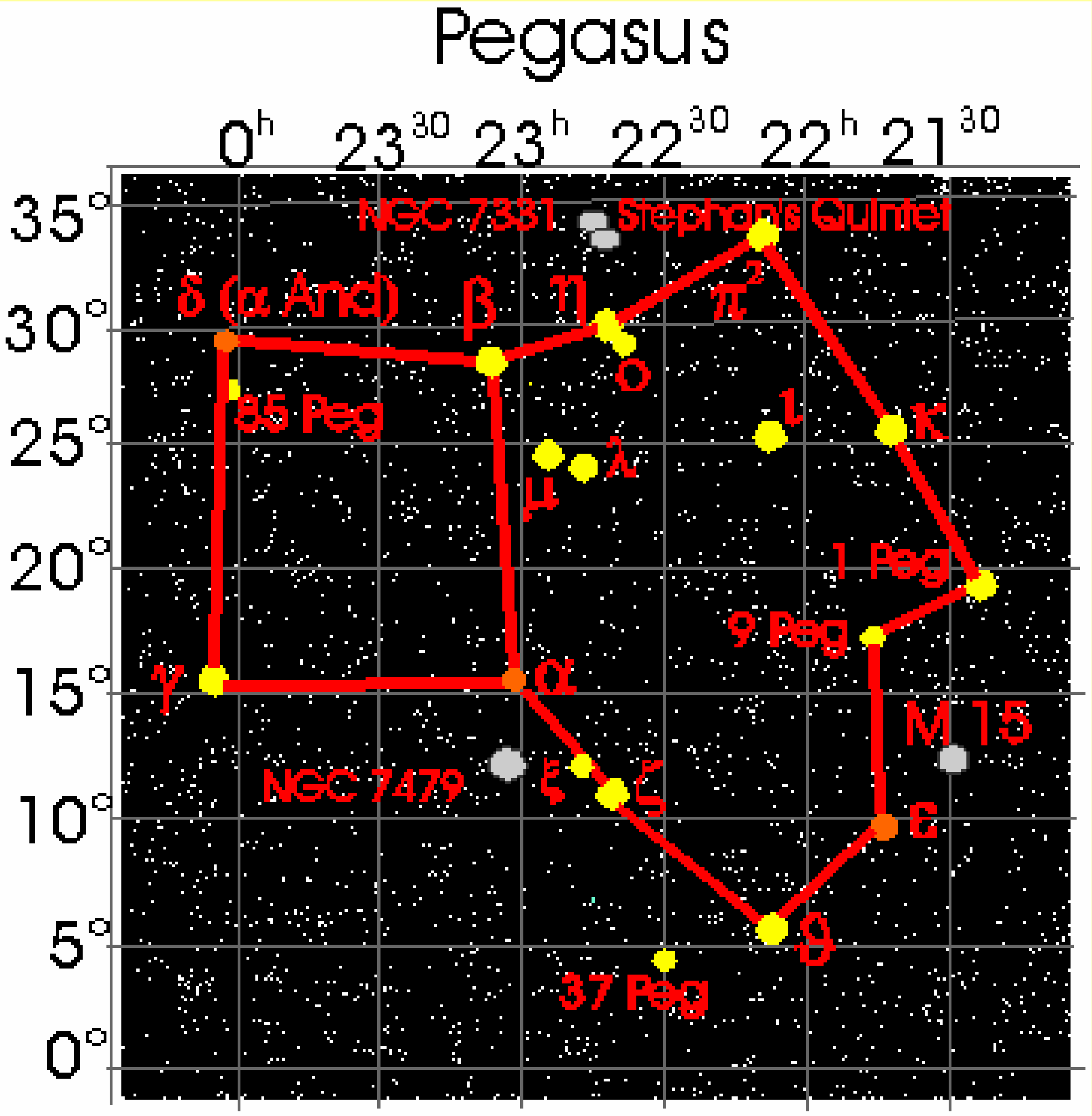
CVn binary σ2 Coronae Borealis



Ne IX
Ne X
Ar XVII
$T = (60\text{-}75).10^3$ K
$n_e = 10^{10} cm^{-3}$

Suh J A, Audard M, Güdel M, Paerels F B S 2005 *Astrophys. J.* **630** 1074--87

Gamma Pegasi (γ Peg)



He I

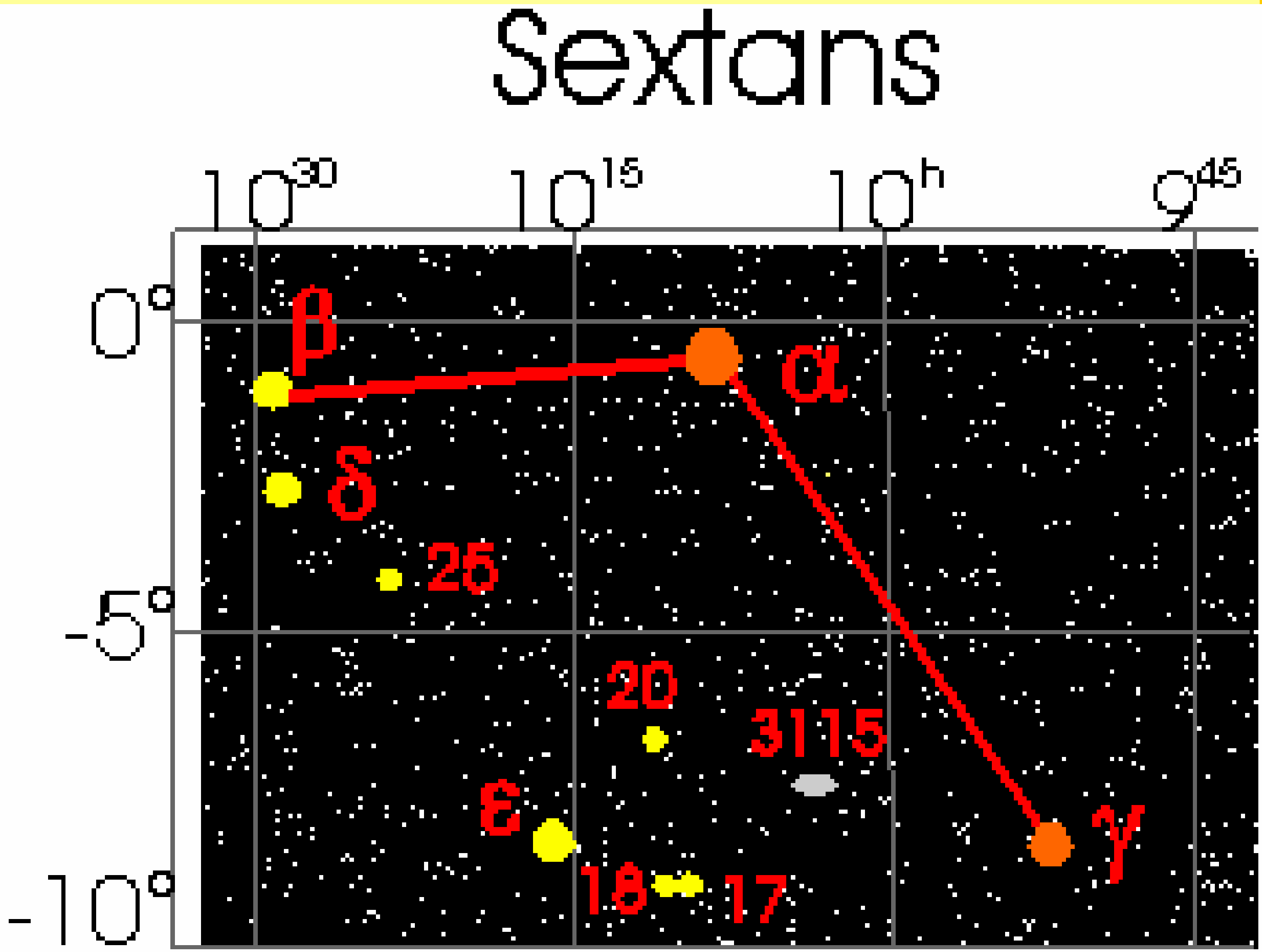
Ne I

Ar II

T_{eff} = 21 500 K

Peters G J 1976 *Astrophys. J. Suppl. Series* **30** 551

Planetary nebulae and H ii regions in the two dwarf irregular galaxies Sextans A and B



Ne IX

Ne X

Ar XVII

$T = (60\text{-}75).10^3$ K

$n_e = 10^{10} cm^{-3}$

Kniazev A Yu,
Grebel E K,
Pustilnik S A,
Pramskij A G,
Zucker D B 2005
Astron. J. **130**
1558--73

Motivation:

The modeling of astrophysical plasma needs of many atomic data, including Stark broadening parameters.

Factors governing the broadening of spectral lines in plasmas

- **plasma environment**
- **atomic structure of emitting atom**

Observed regularities in atomic data

- wave lengths and energy levels
- oscillator strengths
- collision cross sections
- other quantities

Regularities and similarities of the atomic structure

regularities and similarities of the width and shift parameters of plasma broadened lines

⇒ **Accurate interpolation and extrapolation for new results**

Theoretical results for Stark broadening parameters of argon lines from one spectral series

522.1 nm	**$^2[7/2]_4 - {}^2[5/2]_3$**
549.6 nm	**$^2[7/2]_4^{\circ} - {}^2[5/2]_3$**
603.2 nm	**$^2[7/2]_4^{\circ} - {}^2[5/2]_3$**
737.2 nm	**$^2[7/2]_4^{\circ} - {}^2[5/2]_3$**

visible optical Ar I lines

Sahal-Bréshot theory

Semi-classical theory within impact approximation

$$W = 2n_e \int_0^\infty \mathrm{v} f(\mathrm{v}) d\mathrm{v} \left[\sum_{i' \neq i} \sigma_{ii'}(\mathrm{v}) + \sum_{f' \neq f} \sigma_{ff'}(\mathrm{v}) + \sigma_{el} \right]$$

$$d = n_e \int_0^\infty \mathrm{v} f(\mathrm{v}) d\mathrm{v} \int_{\rho_3}^{\rho_d} 2\pi\rho d\rho \sin 2\varphi_p$$

$$\sum_{i' \neq i} \sigma_{ii'}(\mathrm{v}) = \frac{1}{2}\pi\rho_1^2 + \int_{\rho_1}^{\rho_D} 2\pi\rho \, d\rho \sum_{i' \neq i} P_{ii'}(\rho, \mathrm{v})$$

$$\sigma_{el} = 2\pi\rho_2^2 + \int_{\rho_2}^{\rho_D} 8\pi\rho \, d\rho \sin^2 \sqrt{\varphi_p^2 + \varphi_q^2}$$

$$C_1 = \tau^* W << 1$$

$$C_2 = \frac{W_{in}}{W_{el}}$$

$$C_3 = \frac{W_{upp}}{W_{low}}$$

$$C_4 = \frac{W_{str}}{W} < 1$$

$$C_5 = \frac{W}{(\Delta E_{ii'})_{\min}} << 1$$

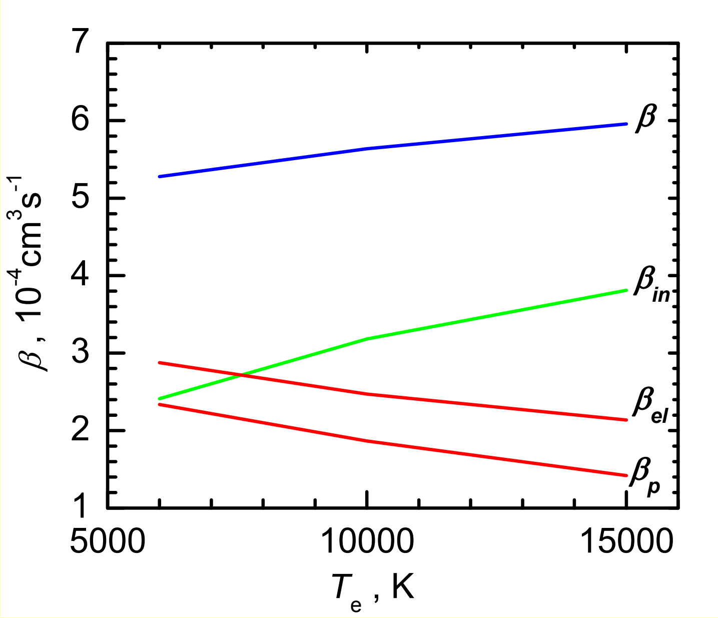
Results for Stark broadening coefficient

$$\beta = \frac{W}{n_e} \qquad \beta = \beta_{in} + \beta_{el} \qquad \beta_{el} = \beta_{el}^{p} + \beta_{el}^{q}$$

Correlation levels
i→i' 20; f→f' 15

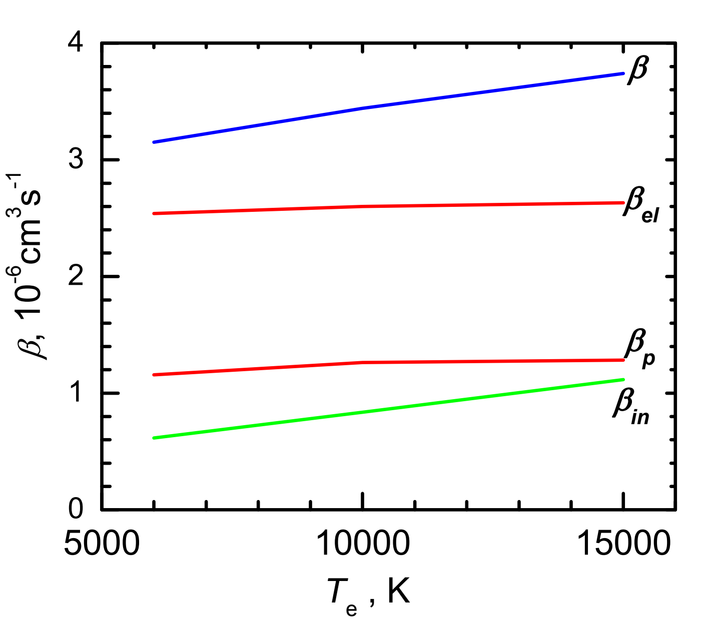
$n_e = 10^{14}$ cm^{-3}
$T_e = (5-15)\times10^3$ K

Ar I 522.1 nm



549.6 nm
603.2 nm
737.2 nm

Ar I 696.5 nm



Similarity of the β-dependence by T_e:

$$T_e \uparrow \rightarrow \begin{cases} \beta_{in} \uparrow \quad \beta \uparrow \\ \beta_{in} > \beta_{el} \\ \beta_{el} \downarrow \quad \beta_p \downarrow \end{cases}$$

$$n^* \uparrow \qquad \beta_p \uparrow$$

broadening of the electrons 85%

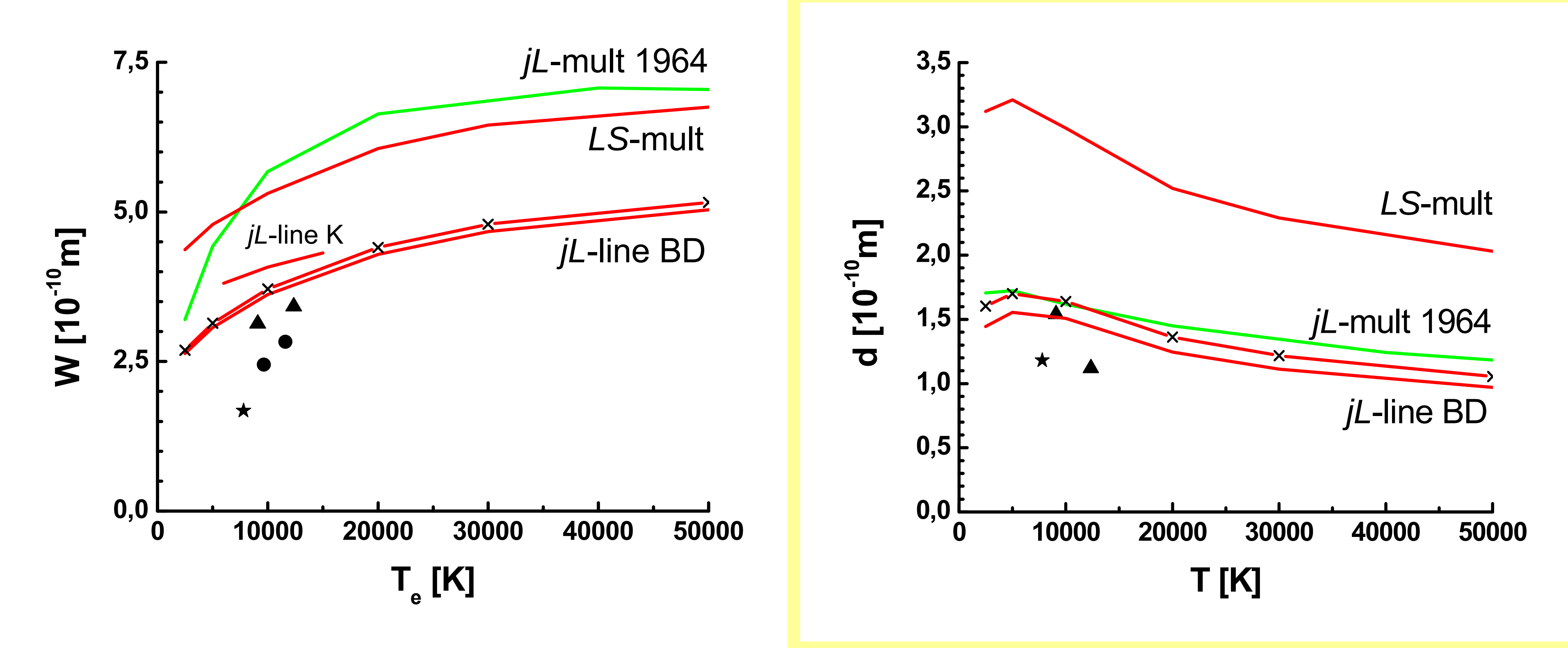
$n^* \downarrow$ ion contribution up to 30%

$$T_e \uparrow \rightarrow \begin{cases} \beta_{el} \cong 4\beta_{in} \\ \beta_p \uparrow \quad \beta_{el} \uparrow \\ \beta_p \approx 0{,}5\beta_{el} \\ \beta_{in} \uparrow \quad \beta \uparrow \end{cases}$$

The contribution of inelastic collisions - entirely by the electrons

Comparison with experimental and theoretical results by other authors

Ar I 549.6 nm



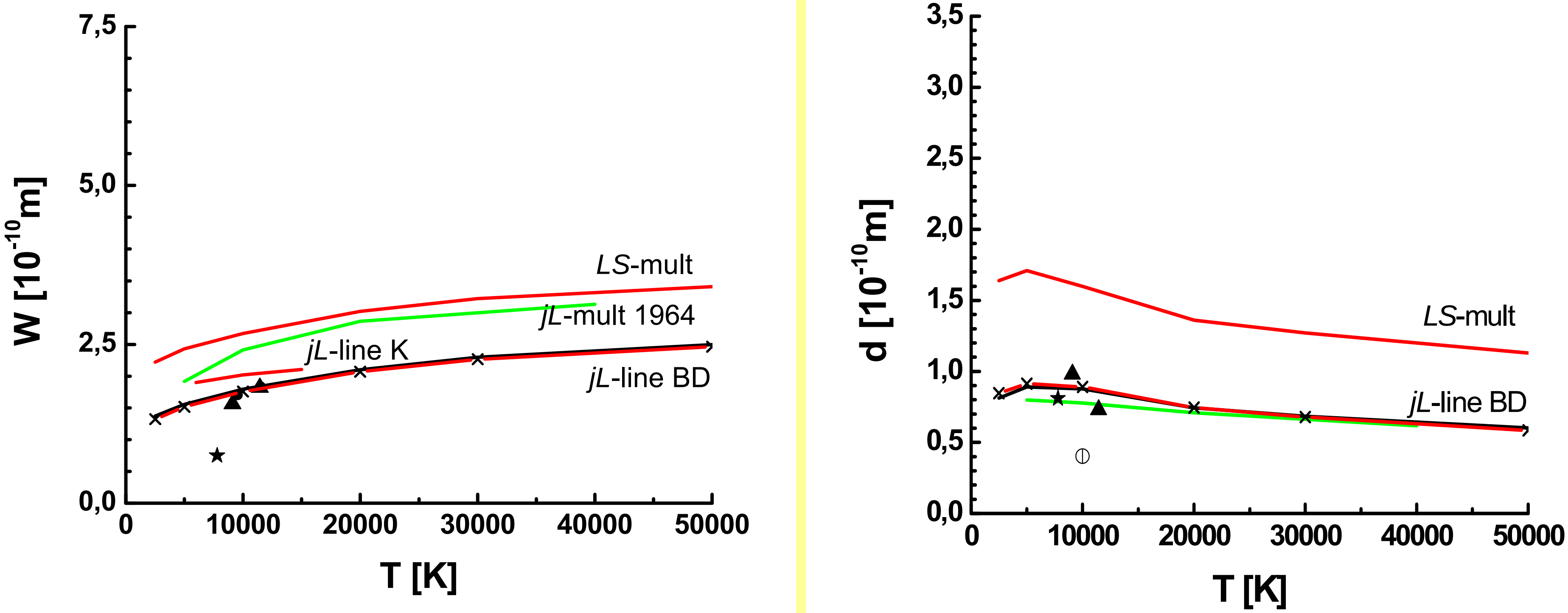
Griem 1974

Sahal-Bréchot ❾❺❾ quasistatic ions

●Schulz 1968; ▲ Bues 1969; ☒Ranson 1974

Comparison with experimental and theoretical results by other authors

Ar I 603.2 nm



Griem 1974

Sahal-Bréchot ❾❺❾ quasistatic ions

●Schulz 1968; ▲ Bues 1969; ☒Ranson 1974; ♦ Kasakov 1981

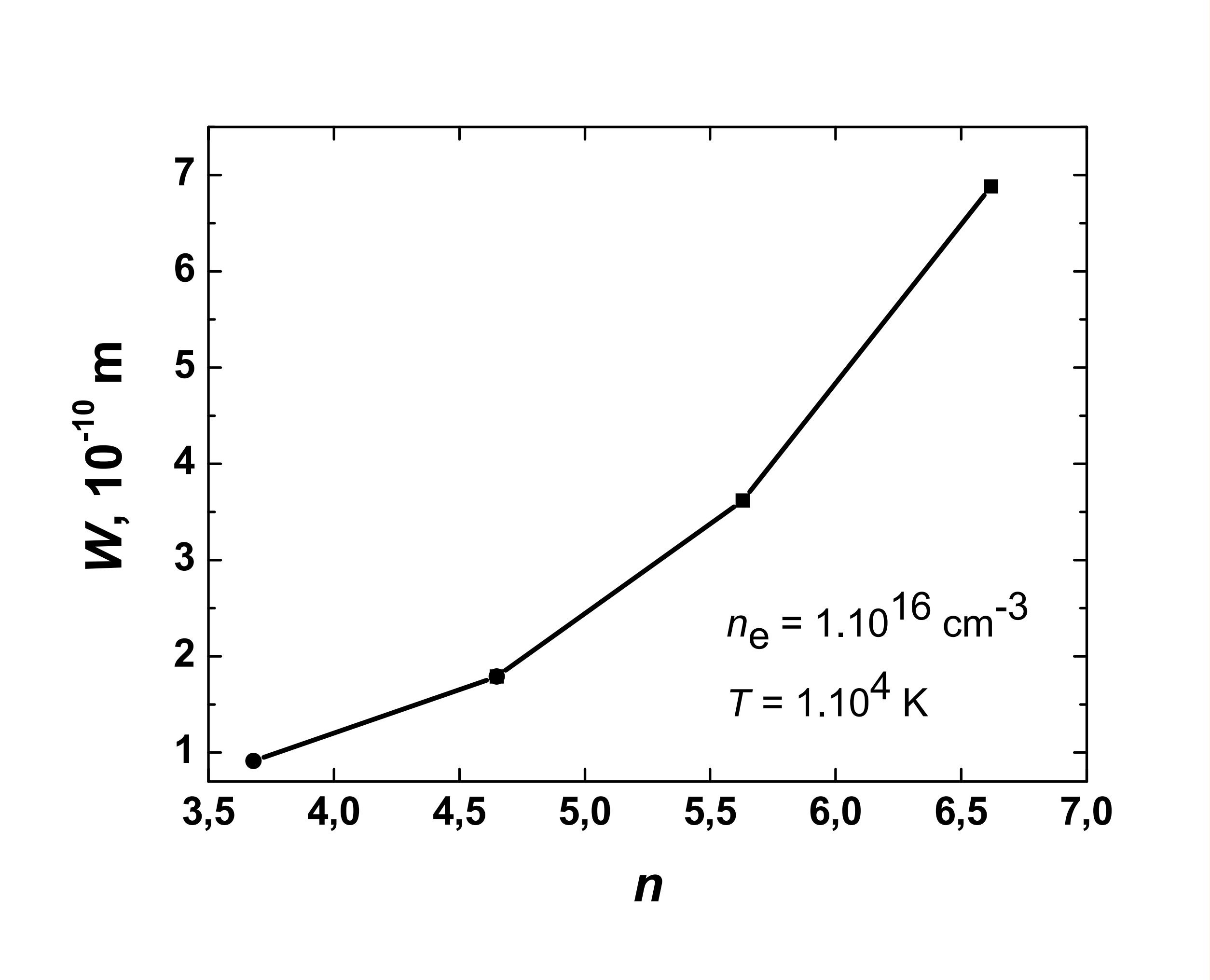
Results for the Stark shift

λ nm	d Å	d_e / d%	d_i / d%
522.1	2.39	85	15
549.6	1.51	85	15
603.2	0.88	86	14
737.2	0.52	86	14

$n_e = 10^{14}$ cm^{-3}
$T_e = 1\times10^4$ K

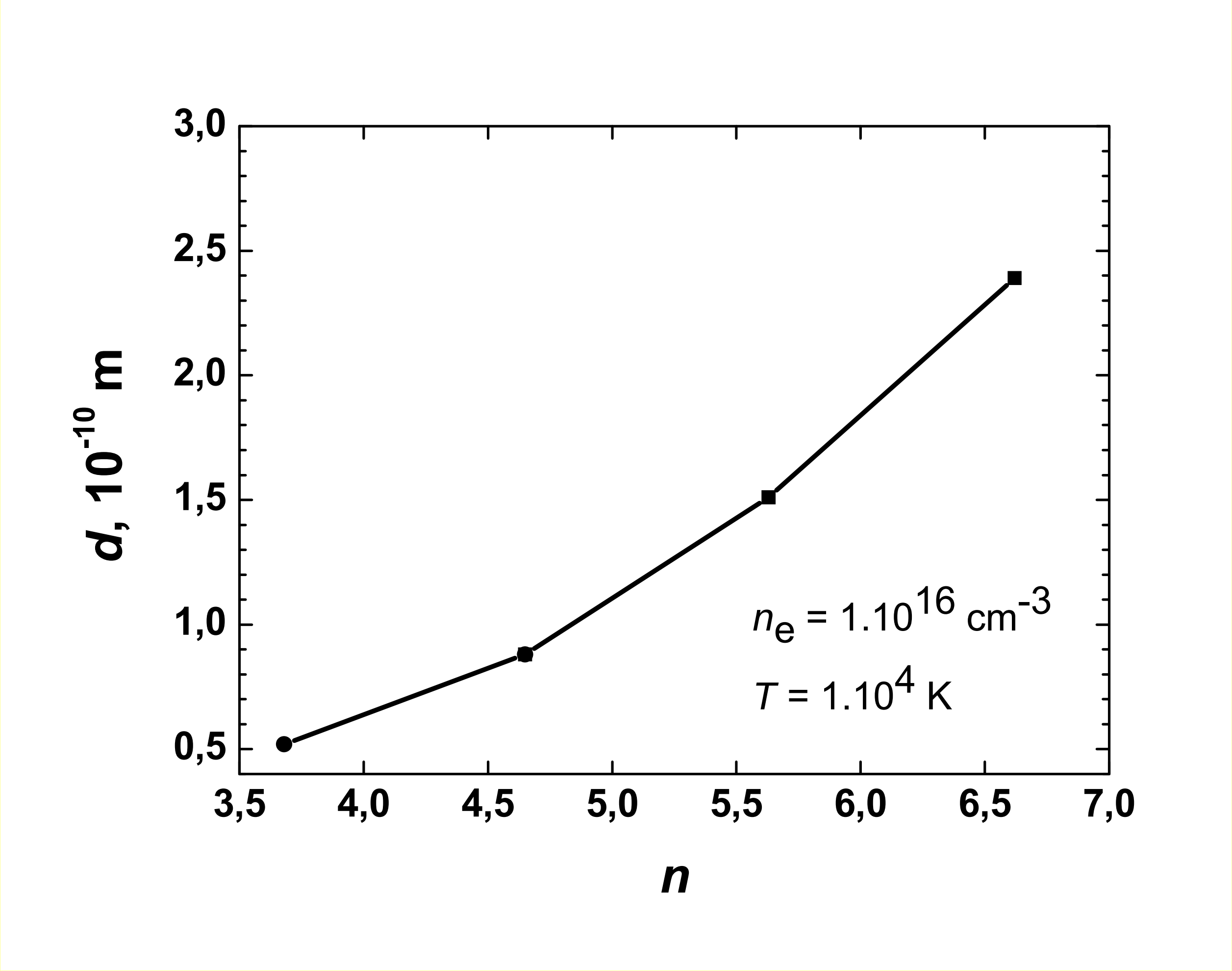
M. S. Dimitrijević, M. Christova and S. Sahal-Bréchot
Phys. Scripta (2007) **75** 809-819

Results: Stark width of lines from one spectral series versus effective quantum number



M Christova, M S. Dimitrijević, A Kovačević
Journal of Physics: Conference Series – in press

Results: Stark shift of lines from one spectral series versus effective quantum number



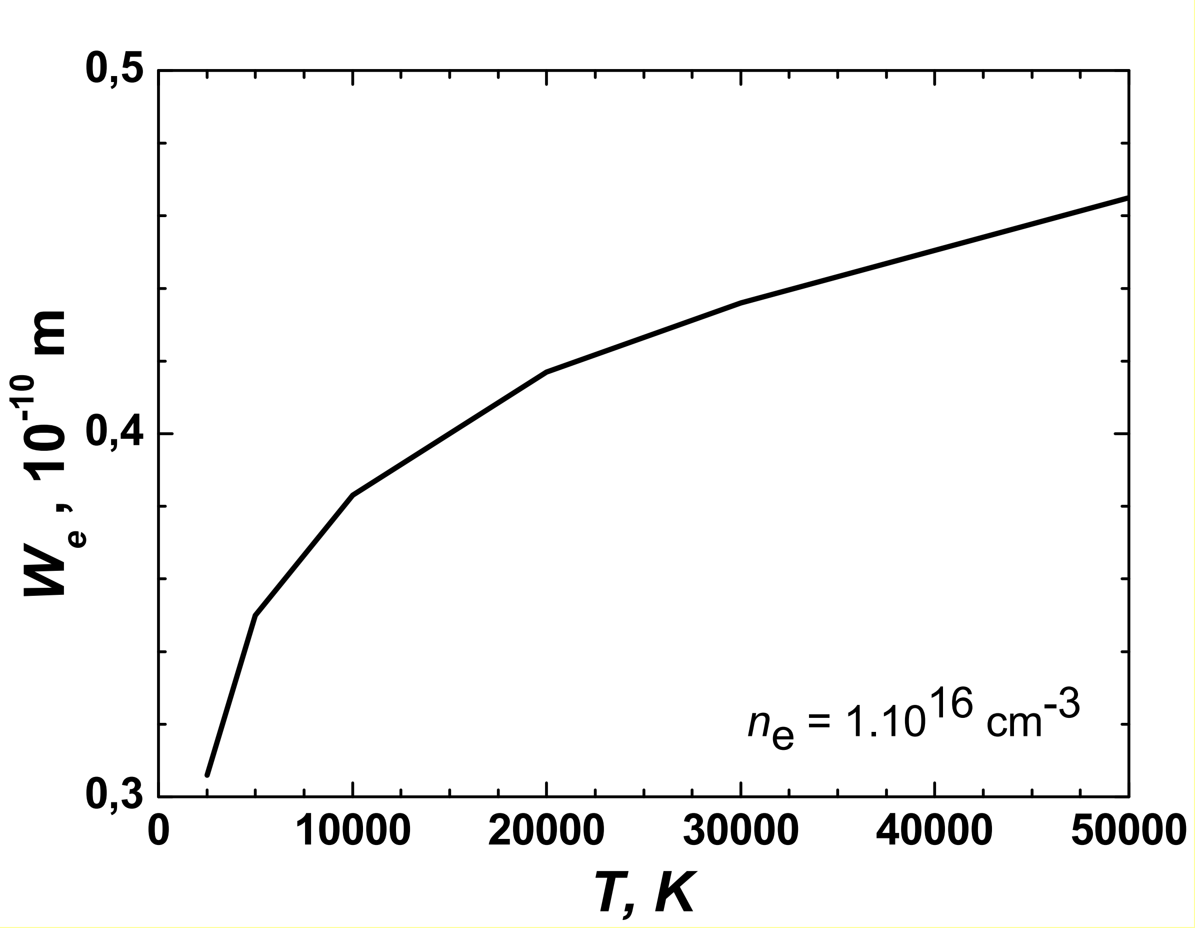
M Christova, M S. Dimitrijević, A Kovačević
Journal of Physics: Conference Series – in press

Results for Ne I 837.7 nm

Basic data for the considered Ne I spectral line. Here λ denotes wavelength, i and f are initial and final level of the transition (within the frame of *j-L* coupling), i' and f' are the corresponding perturbing levels, E_i and E_f are the energy values and n* is the effective quantum number of the initial level.

λ nm	Transition (i - f)	i' levels	f' levels	E_i cm^{-1}	E_f cm^{-1}	n*
837.7	$2p^5 3d' - 2p^5 3p$ $^2[7/2]^\circ_4 - {}^2[5/2]_3$	4f, 5f, 3p, 4p, 5p	3s, 4s, 5s, 3d, 4d, 5d	161590.3	149657.0	2.98

Results for Ne I 837.7 nm



M Christova, M S. Dimitrijević, Z Simić, S Sahal-Bréchot
Journal of Physics: Conference Series – in press

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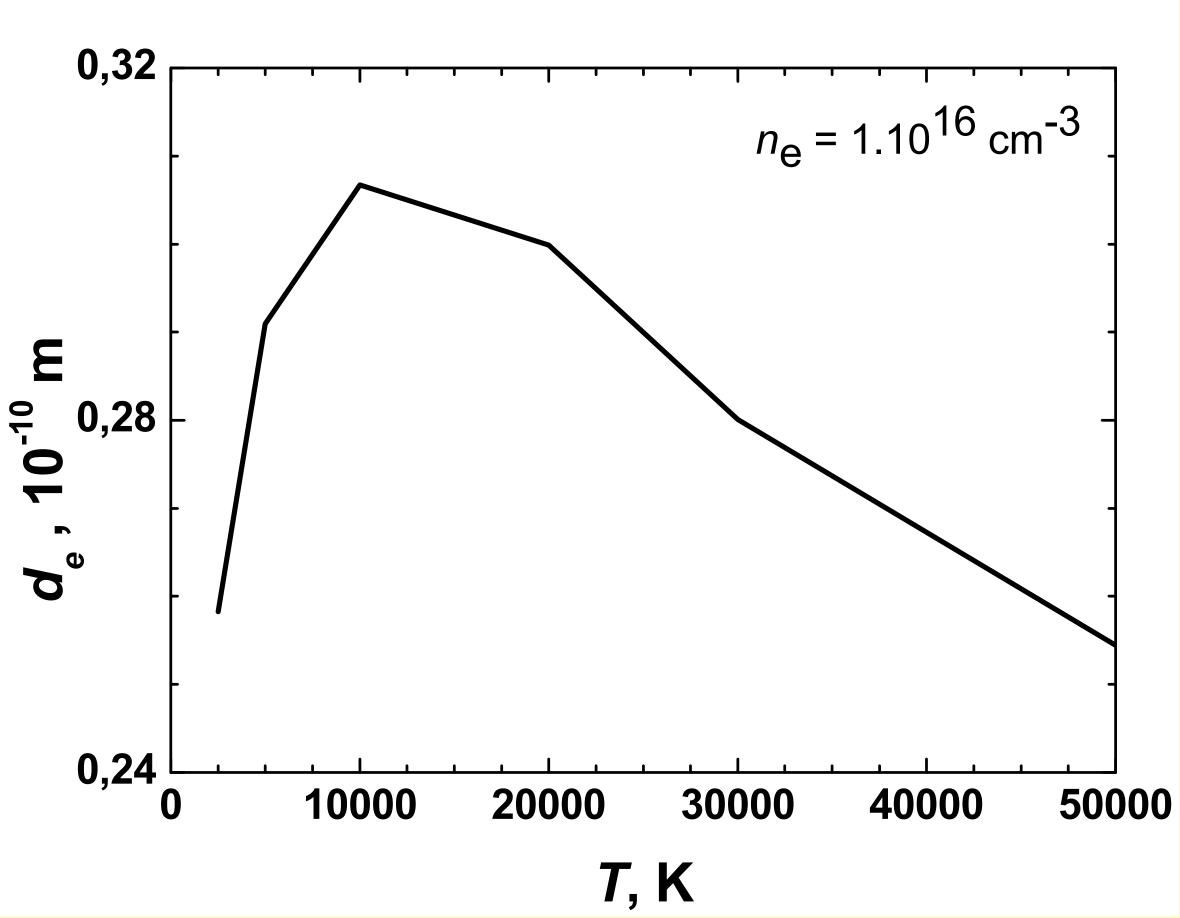

M Christova, M S. Dimitrijević, Z Simić, S Sahal-Bréchot
Journal of Physics: Conference Series – in press

Ευχαριστώ!

Acknowledgments

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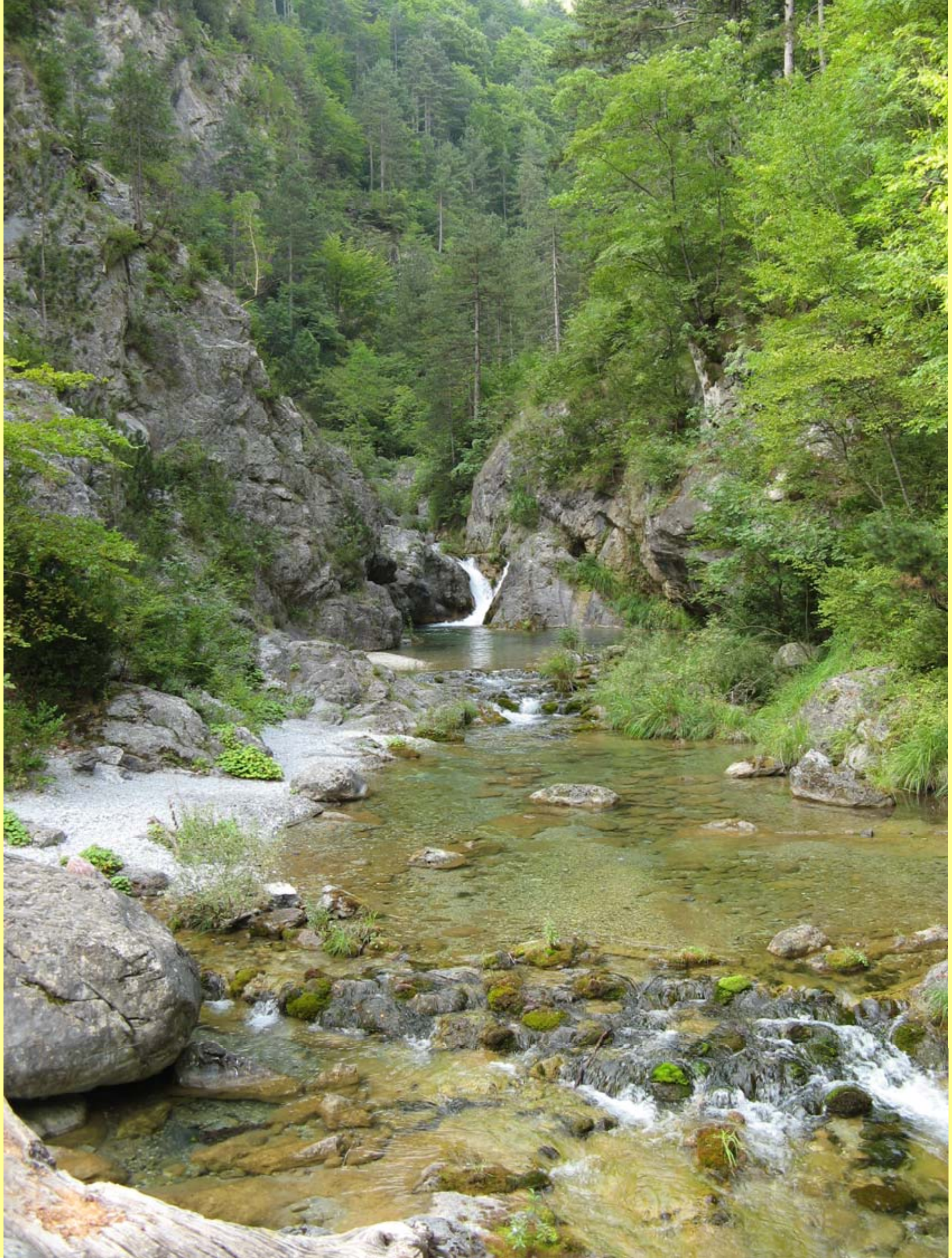
Litochoro

Canyon of Litochoro



Canyon of Litochoro

Mythicas

Just one optical phenomenon