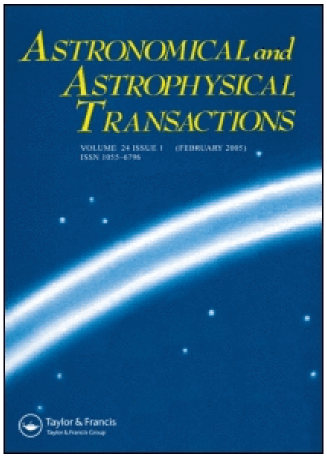

Astronomical & Astrophysical Transactions
The Journal of the Eurasian Astronomical Society
Publication details, including instructions for authors and subscription information:
http://www.informaworld.com/smpp/title~content=t713453505

Stark broadening in astrophysics (applications of Belgrade school results and collaboration with former Soviet republics)

Milan Dimitrijević

Online Publication Date: 01 January 2003
To cite this Article: Dimitrijević, Milan (2003) 'Stark broadening in astrophysics (applications of Belgrade school results and collaboration with former Soviet republics)', Astronomical & Astrophysical Transactions, 22:4, 389 - 412
To link to this article: DOI: 10.1080/1055679031000108167
URL: http://dx.doi.org/10.1080/1055679031000108167

Astronomical and Astrophysical Transactions
Vol. 22, Nos. 4–5, August–October 2003, pp. 389–412

STARK BROADENING IN ASTROPHYSICS (APPLICATIONS OF BELGRADE SCHOOL RESULTS AND COLLABORATION WITH FORMER SOVIET REPUBLICS)

MILAN S. DIMITRIJEVIĆ

Astronomical Observatory, Volgina 7, 11160 Belgrade, Serbia

(Received 27 December 2002)

Stark broadening mechanism for spectral line broadening in astrophysical plasmas is considered and analysed. This line-broadening mechanism is of interest for example for the research on white dwarfs and hot stars of B and A type, for the determination of chemical abundances of elements from equivalent widths of absorption lines, for the estimation of the radiative transfer through the stellar plasmas, especially in subphotospheric layers, and for opacity calculations. Stark broadening is also of significance for research on neutron stars, for investigation of radio recombination lines from molecular and ionised hydrogen clouds, for radiative acceleration considerations, for nucleosynthesis research and for other astrophysical topics. Also, the results of a Stark broadening study in Serbia relevant to astrophysical problems have been reviewed and discussed. Particular attention has been paid to the modified semiempirical method as well as to the use in astrophysics of results and achievements in Stark broadening research of the Belgrade school. The existing collaboration with scientists from former Soviet republics and the results of Serbian scientists in this field applied by our colleagues in their research are considered.

Keywords: Stark broadening; Astrophysics; Plasmas

1 INTRODUCTION

Stark broadening research is a highly developed research field in Yugoslavia, which is studied by a considerable number of scientists and, because of its often interdisciplinary significance, provides a good basis for scientific collaboration. Dimitrijević (1990b; 1991; 1994; 1997a,b; 2001) reviewed spectral line-shape investigations in Yugoslavia and Serbia within the 1962–2000 period; he showed that, during this period, 1427 papers (1222 by Serbian authors) have been published by 179 Yugoslav authors (152 from Serbia, 26 from Croatia and one living in France). The majority of these articles concern Stark broadening. These publications offer also the possibility of considering a much easier collaboration between scientists from the former republics of the Soviet Union and Serbia and of analysing the results of investigations and their applications in order to show possibilities for the development of collaboration. It is interesting to note here that the first paper on Stark broadening published by a Serbian author (M. D. Marinković), noted in the paper by Dimitrijević (1990b), was the result of collaboration with Russian scientists (Mazing et al., 1964). The subject of this research

E-mail: mdimitrijevic@aob.bg.ac.yu

ISSN 1055-6796 print; ISSN 1476-3540 online
DOI: 10.1080/1055679031000108167

was broadening and shift of the Al III spectral lines in strongly ionised plasma. The results of Stark broadening investigations of Belgrade school have been used and cited many times by physicists in former Soviet republics. According to the analysis on the basis of the references given by Dimitrijević (1990b; 1991; 1994; 1997a,b; 2001), the principal users of the results of the Belgrade school are at the Department of Optics and Spectroscopy, Kazan State University. M. Kh. Salakhov, E. V. Sarandaev, O. A. Konovalova, I. S. Fishman, N. A. Grishina and G. G. Il'in used and cited the Stark broadening results of Serbian scientists 202 times. Our results have also been used, for example by V. M. Astashinski, S. A. Babin, G. I. Bakanovich, N. K. Berezheckaya, N. A. Bukova, D. I. Chekhov, A. Derevianko, V. I. Donin, Ya. Ispolatov, G. A. Kobzev, V. A. Kop'ev, I. A. Kossyj, I. I. Kutuzov, A. M. Kuzmickij, A. G. Leonov, A. A. Man'kovskij, L. Ya. Min'ko, A. Oks, A. V. Rodishevskij, D. A. Shapiro, I. I. Sobel'man, A. N. Starostin, M. I. Syrkin, G. M. Tiit, L. A. Vainshtein and E. A. Yukov.

Such results are also of interest for investigations of astrophysical plasmas. The aim of this paper is to analyse the significance of Stark broadening for astrophysical plasma research, to present some achievements of Yugoslav (Serbian) scientists in this field and to consider the existing collaborations and results of Yugoslav (Serbian) scientists applied by our colleagues working in the territory of the former Soviet Union.

2 ASTROPHYSICAL ASPECTS OF THE STARK BROADENING RESEARCH

2.1 Astrophysical Plasma Conditions and Stark Broadening

Nearly 80 years ago, Henry Russel (1926) published in Astrophysical Journal his article with the analysis of the 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'. Johansson (1988), however, stated that, although we now know 675 Fe II energy levels, 50% individual spectral features in high-resolution astrophysical spectra are still unclassified.

This is a consequence of the fact that plasma conditions in astrophysical plasmas are incredibly different in comparison with laboratory plasma sources. Consequently, broadening due to interaction between emitter and charged particles (Stark broadening) is of interest in astrophysics in plasmas of such extreme conditions as in the interstellar molecular clouds or neutron star atmospheres, which cannot be obtained in the laboratory.

In interstellar molecular clouds, typical electron temperatures are around 30 K or lower, and typical electron densities are 2–15 cm^{-3}. In such conditions, free electrons may be captured (recombination) by an ion in a very distant orbit with principal quantum number n values of several hundreds and de-excite in cascade to energy levels $n - 1, n - 2, \ldots$, radiating in the radio domain. Such distant electrons are weakly bound to the core and may be influenced by a very weak electric microfield. Consequently, Stark broadening may be significant (see, for example, Omont and Encrenaz, 1977). In interstellar ionised hydrogen clouds, electron temperatures are around 10,000 K and the electron density is of the order of $10^4\,cm^{-3}$ (Smirnov et al., 1984). Corresponding series of adjacent radio recombination lines originating from energy levels with high (up to several hundreds) n values are influenced by Stark broadening (Smirnov et al., 1984).

For $T_{eff} > 10^4$ K, hydrogen, the main constituent of stellar atmospheres, is mainly ionised and, among collisional broadening mechanisms for spectral lines, the Stark effect is dominant. This is the case for white dwarfs and hot stars of O, B and A type. Even in cooler star atmospheres, for example the solar atmosphere, Stark broadening may be important. For example, the influence of Stark broadening within a spectral series increases with increase in the principal quantum number of the upper level (Dimitrijević and Sahal-Bréchot, 1984a,b; 1985a,b) and, consequently, the Stark broadening contribution may become significant even in the solar spectrum (Vince and Dimitrijević, 1985; Vince et al., 1985a,b).

For example, high-member Balmer series lines may be used as a powerful diagnostic tool in studying stellar atmospheres. Feldman and Doschek (1977) used profiles of Balmer series members with the principal quantum number n between 16 and 32 (strongly influenced by Stark effect) to determine the electron density and the temperature over an active solar region.

The density and temperature ranges of interest for the radiative envelopes of A and F stars are $10^{14}\,\mathrm{cm}^{-3} \leq N_e \leq 10^{16}\,\mathrm{cm}^{-3}$ and $10^4\,\mathrm{K} \leq T \leq 4 \times 10^5\,\mathrm{K}$ (Stehlé, 1994).

White dwarfs have effective temperatures between around 10,000 and 30,000 K so that Stark broadening is of interest for their spectra investigation and plasma research, analysis and modelling. They are divided into two basic groups (see, for example, Beauchamp et al., 1997): DA type, whose spectra are characterised by broad hydrogen lines, and DB type, whose spectra are dominated by the lines of neutral helium. It is interesting that, in white-dwarf spectra, Zeeman broadening, which does not exist in laboratory spectra, has been discovered (Schmidt et al., 1986).

Among the hottest stars are PG1159 stars, hot hydrogen-deficient pre-white dwarfs, with effective temperatures ranging from $T_{\mathrm{eff}} = 100{,}000\,\mathrm{K}$ (for PG 1424 + 535 and PG 1707 + 427) to $T_{\mathrm{eff}} = 140{,}000\,\mathrm{K}$ (for PG 1159 − 035 and PG 1520 + 525), where of course Stark broadening is very important (Werner et al., 1991). These stars have a high surface gravity ($\log g = 7$), and their photospheres are dominated by helium and carbon with a significant amount of oxygen present (a carbon-to-helium ratio of 0.5 and an oxygen-to-helium ratio of 0.13) (Werner et al., 1991). Their spectra, strongly influenced by Stark broadening, are dominated by He II, C IV, O VI and N V lines.

The densities of matter and electron concentrations and temperatures in atmospheres of neutron stars are orders of magnitude larger than in atmospheres of white dwarfs and are typical for stellar interiors. Surface temperatures for the photospheric emission are of the order of 10^6–10^7 K and electron densities of the order of $10^{24}\,\mathrm{cm}^{-3}$ (Madej, 1989; Paerels, 1997). Madej (1989) described the final opacity profile of helium-like iron resonant line by a Voigt profile, with a total damping parameter equal to the sum of natural and Stark (electron-impact) broadening.

2.2 The Need in Astrophysics for an Extensive Set of Stark Broadening Data

It is obvious that stellar spectroscopy depends on a very extensive list of elements and line transitions with their atomic and line-broadening parameters, which is additionally stimulated by the development of space astronomy, since with instruments such as the Goddard high-resolution spectrograph (GHRS) on the Hubble space telescope, an extensive amount of high-quality spectroscopic information has been and will be collected, stimulating the spectral line-shape research. This may be well illustrated by comparison of the χ Lupi UV spectrum obtained with the IUE and GHRS (Fig. 1). One should take into account that, in Figure 1, a part of the spectrum only 2 Å wide is presented and the quality of observed spectral line shapes compared.

Development of computers also stimulates the need for a large amount of atomic and spectroscopic data. A particularly large number of data are needed for example for opacity calculations. An illustrative example might be the article on the calculation of opacities for classical Cepheid models (Iglesias et al., 1990), where 11,996,532 spectral lines have been taken into account. Another good example of the need for an extensive set of atomic and spectroscopic data including Stark broadening is the modelling of stellar atmospheres. For example, the PHOENIX (see Hauschildt and Baron, 1999 and references therein) computer code for stellar modelling includes a database containing 4.2×10^7 atomic or ionic spectral lines.

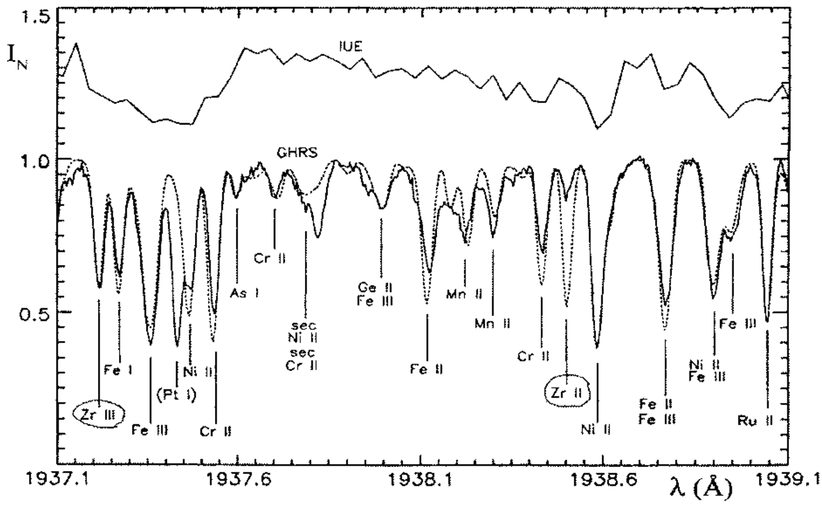

FIGURE 1 The ultraviolet (UV) spectrum of χ Lupi obtained with the GHRS and with the IUE satellite (Leckrone et al., 1993), where the resolution of the spectrum obtained with the GHRS is 0.0023 nm and the maximal signal-to-noise ratio is 95 (Brandt et al., 1999): ———, observed GHRS spectrum; ------, synthesised spectrum.

Interesting investigations, which show the possibilities opened up with the development of computer technology and indicating the need for the largest possible number of spectroscopic and atomic data, are calculations of equivalent width changes in starburst stellar clusters and galaxies with age (Gonzales-Delgado et al., 1999). In this research the changes in particular hydrogen and helium lines equivalent widths during 500 million years have been calculated and compared with observations of stellar clusters and starburst galaxies. Calculations have been made in two steps. Firstly, the population of stars of different spectral types as a function of age are calculated, and then the profiles of the lines are synthesised by adding the different contributions from stars. For spectral line profile synthesis the effects of natural, Stark, neutral atom impact and thermal Doppler broadening have been taken into account.

For the estimation of radiative transfer through stellar plasmas, especially in subphotospheric layers, as well as for the determination of chemical abundances of elements from equivalent widths of absorption lines, a set of Stark broadening data that is as complete as possible for the largest possible number of spectral lines for different emitters is needed, since we do not know a priori the chemical composition of a star.

2.3 Stellar Plasma Research

Line shapes enter the models of radiative envelopes as a result of the estimation of quantities such as the absorption coefficient κ_ν, the Rosseland optical depth τ_{Ross} and the total opacity cross-section $\sigma_\nu(\mathrm{op})$ per atom. Let us take the direction of gravity as the z direction when dealing with a stellar atmosphere. If the atmosphere is in macroscopic mechanical equilibrium and with ρ as the gas density, the optical depth is

$$\tau_\nu = \int_z^\infty \kappa_\nu \rho \, dz, \tag{1}$$

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

where κ_ν is the absorption coefficient at a frequency ν, N(A, i) is the volume density of radiators in the state i, f_{ij} is the absorption oscillator strength, m is the electron mass and ϕ_ν is spectral line profile. The total opacity cross-section per atom is

$$\sigma_\nu(\mathrm{op}) = \mathrm{M}\kappa_\nu, \tag{3}$$

where M is the mean atom mass, and the opacity per unit length is

$$\rho\kappa_\nu = \mathrm{N}\sigma_\nu(\mathrm{op}). \tag{4}$$

Let us introduce an independent variable, a mean optical depth

$$\tau_{\mathrm{Ross}} = \int_z^\infty \kappa_{\mathrm{Ross}}\rho\, \mathrm{d}z. \tag{5}$$

For the Rosseland mean optical depth τ_{Ross}, κ_{Ross} is defined as

$$\frac{1}{\kappa_{\mathrm{Ross}}}\int_0^\infty \frac{\mathrm{dB}_\nu}{\mathrm{dT}}\,\mathrm{d}\nu = \int_0^\infty \frac{1}{\kappa_\nu}\frac{\mathrm{dB}_\nu}{\mathrm{dT}}\,\mathrm{d}\nu, \tag{6}$$

where

$$\mathrm{B}_\nu(\mathrm{T}) = \frac{2\mathrm{h}\nu^3}{\mathrm{c}^2}(\mathrm{e}^{\mathrm{h}\nu/\mathrm{kT}} - 1)^{-1}. \tag{7}$$

Now the Rosseland mean opacity cross-section is

$$\sigma_{\mathrm{Ross}} = \mathrm{M}\kappa_{\mathrm{Ross}}. \tag{8}$$

Stark broadening parameters are needed as well for the determination of the chemical composition of stellar atmospheres, that is for the determination of stellar elemental abundances. The method which uses synthetic and observed spectra and adjustment of atmospheric model parameters to obtain the best agreement is well developed and applied to many stars. It has been found that chemically peculiar stars exist especially within the spectral class interval F0–B2 (Khokhlova, 1994) with abundances for particular elements that are several orders of magnitude different from the solar values. It has also been found that the surfaces of CP stars are chemically inhomogeneous so that a local chemical composition depending on the coordinates on the stellar surface has been introduced (Vogt et al., 1987; Khokhlova, 1994). Such anomalies are explained mainly by the diffusion mechanism occurring in stellar envelopes and/or atmospheres and differences in the radiative accelerations of particular elements (LeBlanc and Michaud, 1995). The radiative acceleration g_r at ν, in the frequency interval dν, acting on element A (with density N(A) and mass m_A) is (Stehlé, 1995)

$$\mathrm{m_A g_r} = \frac{\kappa_\nu(\mathrm{A})}{\mathrm{N(A)}}\Phi_\nu\frac{\mathrm{d}\nu}{\mathrm{c}}, \tag{9}$$

where κ_ν(A) is the contribution of A to the monochromatic absorption coefficient, and Φ_ν is the radiative flux. In the opaque envelope of radius r, the radiative flux is approximately given by (Stehlé, 1995)

$$\Phi_\nu = \frac{4\pi}{3}\frac{1}{\rho\kappa_\nu}\frac{\partial \mathrm{B}_\nu}{\partial \mathrm{T}}\left(\frac{-\partial \mathrm{T}}{\partial \mathrm{r}}\right), \tag{10}$$

$$\kappa_\nu = \kappa_\nu(\mathrm{A}) + \kappa_{\mathrm{rest}}, \tag{11}$$

where κ_{rest} is a parameter consisting of other contributions to the total absorption coefficient apart from κ_ν(A). The majority of CP stars are A- and B-type stars where Stark broadening is the main pressure broadening mechanism.

2.4 Neutron Stars

With the improved sensitivity of space-borne X-ray instruments, spectral lines originating from neutron star atmospheres are of increasing interest. Since the characteristic density in the atmosphere is directly proportional to the acceleration of gravity at the stellar surface, measurement of the pressure broadening of absorption lines will yield a direct measurement of M/R^2, where M and R are the stellar mass and radius, respectively. When this is coupled with a measurement of the gravitational red shift (proportional to M/R) in the same, or any other, line or set of lines, the mass and radius can be determined separately. These mass and radius measurements do not involve the distance to star, which is usually poorly determined, or the size of the emitting area (Paerels, 1997).

In order to obtain a rough estimate of the line widths for a neutron star atmosphere, we may evaluate the width produced by the nearest neighbour (at distance r_{nn}). The energy width for the Lyman α line produced by perturbers of charge z is (Paerels, 1997)

$$W_{Stark} = \frac{6a_0 ze^2}{Zr_{nn}^2} = 6\left(\frac{4\pi}{3}\right)^{2/3} \frac{a_0 ze^2}{Z} N_{pert}^{2/3} \text{ eV}. \tag{12}$$

Here, N_{pert} is the density of perturbers and Z the ionic nuclear charge.

Choosing Thomson scattering depth unity as a convenient reference point and integrating the hydrostatic equilibrium equation for an isothermal atmosphere of temperature T, one obtains that the characteristic electron density for a neutron star atmosphere is (Paerels, 1997)

$$N_e = \frac{\mu m_p g}{\sigma_T kT} = 3.4 \times 10^{24} \mu M_{1.4} T_6^{-1} R_6^{-2} \text{ cm}^{-3}. \tag{13}$$

Here, μ is the mean mass per particle in units of the proton mass m_p, g the acceleration of gravity, σ_T the Thomson cross-section, k the Boltzmann constant, $M_{1.4}$ the stellar mass in units of 1.4 solar masses, R_6 the radius in units of 10^6 cm and T_6 the atmospheric temperature in units of 10^6 K.

The Stark width for a hydrogen-dominated plasma ($z = 1$; $N_{pert} = N_e$; $\mu = \frac{1}{2}$), assuming that electron and proton broadening are comparable in the static approximation (Griem et al., 1979) is (Paerels, 1997)

$$W_{Stark} = 163 Z^{-1} M_{1.4}^{2/3} R_6^{-4/3} T_6^{-2/3} \text{ eV}. \tag{14}$$

Paerels (1997) found a typical Stark width of 20 eV for the hydrogen-like oxygen Lyman α line, and a Stark width of 60 eV has been predicted for the oxygen Lyman β line.

3 APPLICATIONS OF THE SEMICLASSICAL METHOD FOR STARK BROADENING RESEARCH IN SERBIA, ASTROPHYSICAL SIGNIFICANCE OF OBTAINED RESULTS AND THE APPLICATION OF OUR RESULTS BY COLLEAGUES FROM FORMER SOVIET REPUBLICS

In spite of the fact that the most sophisticated theoretical method for the calculation of a Stark broadened line profile is the quantum-mechanical strong coupling approach, because of its complexity and numerical difficulties, only a small number of such calculations exist (see, for example, references given by Dimitrijević, 1996). As an example of the contribution of the Belgrade school, the first calculation of Stark broadening parameters within the quantum-mechanical strong coupling method for non-hydrogen neutral emitter spectral lines is for Li I $2s^2$ S–$2p^2$ P^0 transition (Dimitrijević et al., 1981).

In many cases such as complex spectra, heavy elements or transitions between highly excited energy levels, the more sophisticated quantum-mechanical approach is very difficult or even practically impossible to use and, in such cases, the semiclassical approach remains the most efficient method for Stark broadening calculations.

The existing large-scale calculations of Stark broadening parameters were performed by using three different computer codes, basically developed by the following: firstly, by Benett and Griem (1971), Jones et al. (1971), and Griem (1974); secondly, by Sahal-Bréchot (1969a,b); thirdly, by Bassalo et al. (1982).

In order to complete the largest possible number of Stark broadening data needed for astrophysical and laboratory plasma research and stellar opacities calculations we are making a continuous effort to provide Stark broadening data for a large set of atoms and ions. In a series of papers we have performed large-scale calculations of Stark broadening parameters for a number of spectral lines of various emitters (see, for example, Dimitrijević, 1996 and references therein), within the semiclassical perturbation formalism (Sahal-Bréchot, 1969a,b) innovated and updated several times (Fleurier et al., 1977; Dimitrijević et al., 1991a; Dimitrijević and Sahal-Bréchot, 1995a,b; 1996), for transitions when a sufficiently complete set of reliable atomic data exists and a good accuracy of obtained results is expected. Extensive calculations have been performed, up to now (see, for example, Dimitrijević, 1996 and references therein) for a number of radiators.

The semiclassical result obtained have been compared with critically selected experimental data for 13 He I multiplets (Dimitrijević and Sahal-Bréchot, 1985a,b). The agreement between experimental and semiclassical calculations is within the limits of ±20%, which is the predicted accuracy of the semiclassical method (Griem, 1974).

Our semiclassical Stark broadening parameters have been used for different astrophysical problems. For example, Andrievsky et al. (1999) and Korotin et al. (1999) used the paper by Dimitrijević (1997b) for investigations of carbon, nitrogen and oxygen abundances in early B stars. Tsymbal (1991) used semiclassical results on the Stark broadening of C IV lines (Dimitrijević et al., 1991b) for his analysis of He I lines in B star atmospheres. Data on Mg I (Dimitrijević and Sahal-Bréchot, 1994) and Mg II spectral lines (Dimitrijević and Sahal-Bréchot, 1995a,b) have been used by Bayazitov and Saghidulin (1996) for studies of the Stark broadening influence on stellar Mg I and Mg II line intensities, and Stark broadening data on Si II and Si III (Dimitrijević, 1983) have been used by Topil'skaya (1993) for the investigation of the evolutionary status and chemical composition of the atmospheres of He weak stars.

Since helium has the largest cosmic abundance after hydrogen, it is natural that our helium Stark broadening data (Dimitrijević and Sahal-Bréchot, 1984a,b; 1985a,b; 1989; 1991) have often been used for different investigations in astrophysics. They have also been applied by our colleagues from former Soviet republics; for example, by Sahibulin and Shabert (1990) for examination of the role of blending in helium singlet line formation in Bp star atmospheres, by Zaharova (1994) for research on the atmospheres of two Hg–Mn stars with peculiar noble-gas abundances, by Piskunov et al. (1994) and Kuschnig et al. (1995) for research on the atmosphere, helium surface mapping and spectrum variability of ET Andromedae, by Piskunov and Kupka (2001) for studies of model atmospheres with individualized abundances, by Zboril et al. (1997) and Leushin et al. (2000) for investigations of helium abundance in helium-rich stars, by Israelian et al. (1996) for a study of the atmospheric variations of the peculiar B(e) star HD 45677 (FS Canis Majoris), by Valenti and Piskunov (1996) for assessment of a new method for fitting observations with synthetic spectra, by Zaharova and Ryabchikova (1996) for studies of the abundance of the ^{3}He isotope in Hg–Mn star atmospheres, by Kopylov et al. (1989) for examination of criteria of spectral classification and the temperature scale and by Tsymbal (1991) for investigation of neutral helium lines in B star atmospheres.

Our semiclassical Stark broadening results which have the highest impact in astrophysics concern ionised silicon spectral lines. Results of our semiclassical investigations (Lanz et al., 1988) have been used by S. J. Adelman, O. I. Pintaldo, A. G. Davis Philip, H. Caliskan, B. Albayrak, C. Bolcal, G. Hill, D. Kocer, H. G. Tektanali, T. Kay, F. Guliver, Z. Lopez-Garcia, G. M. Walhgren, R. D. Robinson, J. Zverko, M. Zboril, J. Žižnovski, B. Gustafsson, G. Mathys, J. Singh, F. Castelli, T. Lanz, M.-C. Artru, P. Didelon, T. Rauch, P. North and S. Berthet for silicon abundance analyses with co-added Dominion Astrophysical Observatory (DAO) spectrograms of the following: Hg–Mn stars ϕ Herculis, 28 Herculis, HR 7664, ν Cancri, ι Coronae Borealis, HR 8349, π Bootis, ν Herculis, HR 7361, HR 4072 and HR 7775; B stars π Ceti, 134 Tauri, 21 Aquilae, ν Capricorni, γ Pegasi, ι Herculis, ζ Draconis, η Lyrae, 8 Cygni and 22 Cygni; B and A stars γ Geminorum, 7 Sextantis, HR 4817, HR 5780, HD 60825, Merak, π Draconis and κ Cephei; early A-type stars 68 Tauri, 21 Lyncis, α Draconis, 2 Lyncis, ω Ursae Majoris, ϕ Aquilae, 29 Vulpeculae and σ Aquarii; normal F main sequence stars θ Cygni, ι Piscium, σ Bootis; the metallic lined stars 15 Vulpeculae, 32 Aquarii, HR 4072B, 60 Leonis and 6 Lyrrae; silicon abundance analyses with Complejo Astronomico el Leoncito REOSC echelle spectrograms of κ Cancri, HR 7245, ξ Octantis, HR 4487, 14 Hydrae and 3 Centauri A; silicon abundance studies of CP stars HD 43819, HD 147550, χ Lupi, 21 Canum Venaticorum, HD 133029 and HD 192913; silicon abundance determination for γ Geminorum, HR 1397, HR 2154, HR 60825 and 7 Sextantis. Our data have also been used for a discussion on the future of stellar spectroscopy, investigation of blue stragglers of M67, determination of the effective temperature of B-type stars from the Si II lines of the UV multiplet 13.04 at 130.5–130.9 nm, analysis of the red spectrum of Ap stars, a non-local thermodynamical equilibrium (NLTE) analysis of subluminous O-type hot sub-dwarf in the binary system HD 128220 and a discussion of the nature of the F str ($\lambda = 4077$ Å)-type stars. They also have been used by Piskunov et al. (1994) and Kuschnig et al. (1995) for research on the atmosphere, helium surface mapping and spectrum variability of ET Andromedae, by Piskunov et al. (1995; 1999) for the consideration of Vienna atomic line database and by Khokhlova (1994) for a discussion of the role of spectral line Stark shifts for stellar chemical composition determination with the atmospheric model method.

Our data for Ga II (Dimitrijević and Artru, 1986) have been used by Ryabchikova and Smirnov (1994) for gallium abundance analysis of κ Cancri, our data for Ca II (Dimitrijević and Sahal-Bréchot, 1993) have been used by Ryabchikova et al. (1999a) for abundance analyses of the double-lined spectroscopic binary α Andromedae.

4 THE INFLUENCE OF STARK BROADENING AND STRATIFICATION EFFECT ON Si I LINES IN THE roAp STAR 10 Aql

An example of the use of Stark broadening data in astrophysics has been given in the article by Dimitrijević et al. (2003) resulting from a collaboration of the present author and Luka Č. Popović from Serbia, Tanya A. Ryabchikova from Moscow, and Vadim V. Tsymbal and Denis Shulyak from Simferopol.

Dimitrijević et al. (2003) have studied the influence of Stark broadening and stratification effect on Si I lines in the rapidly oscillating (roAp) star 10 Aql, where the Si I (6142.48 and 6155.13 Å) lines are asymmetrical and shifted. Firstly, they have calculated Stark broadening parameters using the semiclassical perturbation method for three Si I lines: 5950.2, 6142.48

and 6155.13 Å. They revised the synthetic spectrum calculations code by taking into account both the Stark width and the shift of these lines. From a comparison of their calculations with the observations, they found that the Stark broadening + stratification effect can explain the asymmetry of the Si I (6142.48 and 6155.13 Å) lines.

For analysis they used observations of one normal star HD 32115, two Ap stars HD 122970 and 10 Aql and the Solar Flux Atlas by Kurucz et al. (1984). High-resolution charge-coupled device (CCD) spectra of 10 Aql and HD 122970 have been described in a paper by Ryabchikova et al. (2000). High-resolution CCD spectra ($R \approx 45{,}000$) of HD 32115 in the wavelength region 4000–9500 Å were obtained with the Coudé echelle spectrometer mounted on the 2 m Zeiss telescope at the Peak Terskol Observatory, Russia (see Bikmaev et al. (2002) for more details).

Many Ap stars show peculiar line profiles of Si I but most stars have rather strong magnetic fields which distort the line profiles through Zeeman splitting. Rather weak magnetic fields in Ap stars HD 122970 and 10 Aql allow us to ignore the magnetic effects on the line shape.

Model atmosphere calculations as well as calculations of the absorption coefficients were made with the local thermodynamic equilibrium (LTE) approximation. Model calculations were performed with the help of the ATLAS9 code written by Kurucz (1993).

The next step was the calculation of the outward flux at corresponding wavelength points using the given model. For this purpose they used the STARSP program written by Tsymbal (1996). In its current state this code includes the possibility of calculating synthetic spectrum for an atmosphere with vertical stratification of chemical elements.

They first calculated Si I lines in the solar spectrum to check the Stark parameters and with the corrected Stark parameters they calculated Si I line profiles in the spectra of HD 32115, HD 122970 and 10 Aql stars.

10 Aql = HD 176232 is the hottest star in their sample. It has the most asymmetrical Si I (6155.13 Å) line profile, which could not be reproduced by any combination of Stark parameters in a homogeneous atmosphere. The even weaker Si I (6142.48 Å) line shows a noticeable line shift. Ryabchikova et al. (2000) mentioned a possibility of Fe and the rare-earth element (REE) stratification in 10 Aql. Therefore they tried to find a simple distribution of Si in the atmosphere of 10 Aql by trial and error which would fit both Si I (6142.48 and 6155.13 Å) lines. The obtained distribution give a reasonable fit to the observed profiles of both Si I lines (Fig. 2).

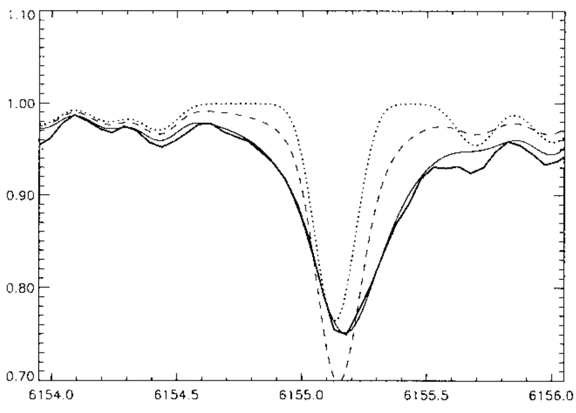

FIGURE 2 A comparison between the observed Si I (6155 Å) line profile in the spectrum of Ap star 10 Aql (———) and the synthetic spectra calculated with Stark widths and shifts from Table I of the paper by Dimitrijević et al. (2003) and silicon abundance stratification (———), with the same Stark parameters but for homogeneous silicon distribution (– – – –), and with Stark width calculated by approximation formulae for the same stratification (· · · · · ·).

Moreover, the same silicon distribution seems to fit much better the profiles of strong Si II (6347 and 6371 Å) spectral lines compared with the calculations with the homogeneous silicon abundance (−4.19) obtained by Ryabchikova et al. (2000). These workers stressed in their analysis that, with the Stark parameters used, a sensitivity of the 6155.13 Å line asymmetry to silicon abundance changes in the stellar atmosphere can be successfully used in empirical studies of abundance stratification in the atmospheres of cool Ap stars.

5 MODIFIED SEMIEMPIRICAL METHOD FOR STARK BROADENING AND ASTROPHYSICAL APPLICATIONS

The modified semiempirical (MSE) approach (Dimitrijević and Konjević, 1980) for the calculation of Stark broadening parameters for non-hydrogen ion spectral lines has been applied successfully many times for different problems in astrophysics and physics. According to the MSE approach (Dimitrijević and Konjević, 1980; 1981; 1987; Dimitrijević and Kršljanin, 1986; Dimitrijević and Popović, 1993; 2001; Popović and Dimitrijević, 1996a) the electron impact full width at half-maximum (FHWM) of an isolated ion line is given as

$$w_{MSE} = N\frac{4\pi}{3c}\frac{\hbar^2}{m^2}\left(\frac{2m}{\pi kT}\right)^{1/2}\frac{\lambda^2}{3^{1/2}}\cdot\left[\sum_{\ell_i\pm 1}\sum_{L_{i'}J_{i'}}\mathfrak{R}^2_{\ell_i,\ell_i\pm 1}\tilde{g}(x_{\ell_i,\ell_i\pm 1}) + \sum_{\ell_f\pm 1}\sum_{L_{f'}J_{f'}}\mathfrak{R}^2_{\ell_f,\ell_f\pm 1}\tilde{g}(x_{\ell_f,\ell_f\pm 1})\right.$$
$$\left. + \left(\sum_{i'}\mathfrak{R}^2_{ii'}\right)_{\Delta n\neq 0} g(x_{n_i,n_i+1}) + \left(\sum_{f'}\mathfrak{R}^2_{ff'}\right)_{\Delta n\neq 0} g(x_{n_f,n_f+1})\right], \quad (15)$$

and the corresponding Stark shift as

$$d = N\frac{2\pi}{3c}\frac{\hbar^2}{m^2}\left(\frac{2m}{\pi kT}\right)^{1/2}\frac{\lambda^2}{3^{1/2}}\left[\sum_{L_{i'}J_{i'}}\sigma_{J_iJ_{i'}}\mathfrak{R}^2_{\ell_i,\ell_i+1}\tilde{g}_{sh}(x_{\ell_i,\ell_i+1})\right.$$
$$-\sum_{L_{i'}J_{i'}}\sigma_{J_iJ_{i'}}\mathfrak{R}^2_{\ell_i,\ell_i-1}\tilde{g}_{sh}(x_{\ell_i,\ell_i-1})\sum_{L_{f'}J_{f'}}\sigma_{J_fJ_{f'}}\mathfrak{R}^2_{\ell_f,\ell_{f+1}}\tilde{g}_{sh}(x_{\ell_f,\ell_f+1})$$
$$+\sum_{L_{f'}J_{f'}}\sigma_{J_fJ_{f'}}\mathfrak{R}^2_{\ell_f,\ell_{f-1}}\tilde{g}_{sh}(x_{\ell_f,\ell_f-1}) + \left(\sum_{i'}\mathfrak{R}^2_{ii'}\right)_{\Delta n\neq 0} g_{sh}(x_{n_i,n_i+1})$$
$$-2\sum_{i'(\Delta E_{ii'}<0)}\sum_{L_{i'}J_{i'}}\mathfrak{R}^2_{\ell_i,\ell_{i'}}g_{sh}(x_{\ell_i,\ell_{i'}}) - \left(\sum_{f'}\mathfrak{R}^2_{ff'}\right)_{\Delta n\neq 0} g_{sh}(x_{n_f,n_f+1})$$
$$\left.+2\sum_{f'(\Delta E_{ff'}<0)}\sum_{L_{f'}J_{f'}}\mathfrak{R}^2_{\ell_f,\ell_{f'}}g_{sh}(x_{\ell_f,\ell_{f'}}) + \sum_k \delta_k\right], \quad (16)$$

where the initial level is denoted by i, and the final level by f, $\mathfrak{R}^2_{\ell_k,\ell_{k'}}$, $k = i, f$ is the square of the matrix element, and

$$\left(\sum_{k'}\mathfrak{R}^2_{kk'}\right)_{\Delta n\neq 0} = \left(\frac{3n_k^*}{2Z}\right)^2\frac{1}{9}(n_k^{*2} + 3\ell_k^2 + 3\ell_k + 11) \quad (17)$$

(in the Coulomb approximation).

In Eqs. (15) and (16),

$$x_{\ell_k,\ell_{k'}} = \frac{E}{\Delta E_{\ell_k,\ell_{k'}}}, \quad k = i, f,$$

where $E = \frac{3}{2}kT$ is the electron kinetic energy and $\Delta E_{\ell_k,\ell_{k'}} = |E_{\ell_k} - E_{\ell_{k'}}|$ is the energy difference between levels ℓ_k and $\ell_k \pm 1$ ($k = i, f$),

$$x_{n_k,n_k+1} \approx \frac{E}{\Delta E_{n_k,n_k+1}},$$

where for $\Delta n \neq 0$ the energy difference $\Delta E_{n_k,n_k+1}$ between energy levels with n_k and $n_k + 1$ is estimated as $\Delta E_{n_k,n_k+1} \approx 2Z^2E_H/n_k^{*3}$; $n_k^* = [E_H Z^2/(E_{ion} - E_k)]^{1/2}$ is the effective principal quantum number, Z is the residual ionic charge, for example $Z = 1$ for neutral atoms, and E_{ion} is appropriate spectral series limit.

In Eqs. (15)–(17), N and T are the electron density and temperature respectively, while g(x) (Griem, 1968), $\tilde{g}(x)$ (Dimitrijević and Konjević, 1980) and $g_{sh}(x)$ (Griem, 1968), $\tilde{g}_{sh}(x)$ (Dimitrijević and Kršljanin, 1986) denote the corresponding Gaunt factors for width and shift respectively. The factor $\sigma_{kk'} = (E_{k'} - E_k)/|E_{k'} - E_k|$, where E_k and $E_{k'}$ are the energies of the considered level and its perturbing level, respectively. The sum $\sum_k \delta_k$ is different from zero only if perturbing levels that strongly violate the assumed approximations exist and may be evaluated as

$$\delta_i = \pm \mathfrak{R}_{ii'}^2 \left[g_{sh}\left(\frac{E}{\Delta E_{i,i'}}\right) \mp g_{sh}(x_{n_i,n_i+1}) \right], \tag{18}$$

for the upper level, and

$$\delta_f = \mp \mathfrak{R}_{ff'}^2 \left[g_{sh}\left(\frac{E}{\Delta E_{f,f'}}\right) \mp g_{sh}(x_{n_f,n_f+1}) \right], \tag{19}$$

for the lower level. In Eqs. (18) and (19) the lower signs correspond to $\Delta E_{jj'} < 0$.

In comparison with the full semiclassical approach (Sahal-Bréchot, 1969a,b; Griem, 1974) and the Griem (1968) semiempirical approach which needs almost the same set of atomic data as the more sophisticated semiclassical method, the MSE approach (Dimitrijević and Konjević, 1980; 1981; 1987; Dimitrijević and Kršljanin, 1986; Dimitrijević and Popović, 1993; 2001; Popović and Dimitrijević, 1996a) needs a considerably smaller number of such data. In fact, if there are no perturbing levels that strongly violate the assumed approximation, for example linewidth calculations, we need only the energy levels with $\Delta n = 0$ and $\ell_{if} = \ell_{if} \pm 1$, since all perturbing levels with $\Delta n \neq 0$ needed for a full semiclassical investigation or an investigation within the Griem (1968) semiempirical approach are lumped together and approximately estimated. Here, n is the principal quantum number and ℓ the orbital angular momentum quantum numbers of the optical electron; i and f denote the initial and final states, respectively, of the considered transition.

Because of the considerably smaller set of atomic data needed in comparison with the complete semiclassical (Sahal-Bréchot, 1969a,b; Griem, 1974) or the Griem (1968) semiempirical methods, the MSE method is particularly useful for stellar spectroscopy depending on the very extensive list of elements and line transitions with their atomic and line-broadening parameters where it is not possible to use sophisticated theoretical approaches in all cases of interest.

The MSE method is also very useful whenever line-broadening data for a large number of lines are required, and the high precision of every particular result is not so important, for example for opacity calculations or plasma modelling. Moreover, in the case of more complex atoms or multiply charged ions the lack of accurate atomic data needed for more sophisticated calculations makes the reliability of the semiclassical results decreases. In such cases the MSE method might be very interesting as well.

6 SIMPLIFIED MODIFIED SEMIEMPIRICAL FORMULA

For astrophysical purposes, of particular interest might be the simplified semiempirical formula (Dimitrijević and Konjević, 1987) for Stark widths of isolated, single and multiple charged ion lines applicable in the cases when the nearest atomic energy level ($j' = i'$ or f') where a dipole allowed transition can occur from or to the initial (i) or final (f) energy level of the considered line in so far that the condition $x_{jj'} = E/|E_{j'} - E_j| \leq 2$ is satisfied. In such a case the FWHM is given by the expression (Dimitrijević and Konjević, 1987)

$$W(\text{Å}) = 2.2151 \times 10^{-8} \frac{\lambda^2(\text{cm})N(\text{cm}^{-3})}{T^{1/2}(\text{K})}\left(0.9 - \frac{1.1}{Z}\right)\sum_{j=i,f}\left(\frac{3n_j^*}{2Z}\right)^2 (n_j^{*2} - \ell_j^2 - \ell - 1). \quad (20)$$

Here, $E = 3kT/2$ is the energy of the perturbing electron, $Z - 1$ is the ionic charge and n is the effective principal quantum number. This expression is of interest for abundance calculations, as well as for stellar atmospheres research, since the validity conditions are often satisfied for stellar plasma conditions.

Similarly, in the case of the shift

$$d(\text{Å}) = 1.1076 \times 10^{-8} \frac{\lambda^2(\text{cm})N(\text{cm}^{-3})}{T^{1/2}(\text{K})}\left(0.9 - \frac{1.1}{Z}\right)\frac{9}{4Z^2} \times \sum_{j=i,f} \frac{n_j^{*2}\varepsilon_j}{2\ell_j + 1}\left\{(\ell_j + 1)[n_j^{*2} - (\ell_j + 1)^2] - \ell_n(n_j^{*2} - \ell_j^2)\right\}. \quad (21)$$

If all levels $\ell_{i,f} \pm 1$ exist, an additional summation may be performed in Eq. (21) to obtain

$$d(\text{Å}) = 1.1076 \times 10^{-8} \frac{\lambda^2(\text{cm})N(\text{cm}^{-3})}{T^{1/2}(\text{K})}\left(0.9 - \frac{1.1}{Z}\right)\frac{9}{4Z^2} \times \sum_{j=i,f} \frac{n_j^{*2}\varepsilon_j}{2\ell_j + 1}(n_j^{*2} - 3\ell_j^2 - 3\ell_j - 1), \quad (22)$$

where $\varepsilon = +1$ for $j = i$ and -1 for $j = f$.

The MSE approach has been tested several times on numerous examples (Dimitrijević, 1990a). In order to test this method, selected experimental data for 36 multiplets (seven different ion species) of triply charged ions were compared with theoretical linewidths. The averaged values of the ratios of measured to calculated widths are as follows (Dimitrijević and Konjević, 1980): for doubly charged ions, 1.06 ± 0.32; for triply charged ions, 0.91 ± 0.42. The assumed accuracy of the MSE approximation is about ±50%, but it has been shown by Popović and Dimitrijević (1996b; 1998) and Dimitrijević and Popović (2001) that the MSE approach, even in the case of the emitters with very complex spectra (e.g. Xe II and Kr II), gives very good agreement with experimental measurements (in the interval ±30%). For example, for Xe II 6s–6p transitions, the averaged ratio of experimental to theoretical widths is 1.15 ± 0.5 (Popović and Dimitrijević, 1996b).

7 APPLICATIONS OF OBTAINED RESULTS

The MSE method and Stark broadening parameters calculated within this approach have been applied in astrophysics, for example for the determination of carbon, nitrogen and oxygen abundances in early B-type stars (Gies and Lambert, 1992), magnesium, aluminium and silicon abundances in normal late B and Hg–Mn stars, from co-added IUE spectra (Smith, 1993) and elemental abundances in hot white dwarfs (Chayer et al., 1995a,b), investigations of abundance anomalies in stars (Michaud and Richer, 1992), elemental abundance analyses with DAO spectrograms for 15 Vulpeculae and 32 Aquarii (Bolcal et al., 1992), radiative acceleration calculation in stellar envelopes (Alecian et al., 1993; Gonzales et al., 1995a,b; LeBlanc and Michaud, 1995; Seaton, 1997), consideration of radiative levitation in hot white dwarfs (Chayer et al., 1995a,b; Charo et al., 1999), quantitative spectroscopy of hot stars (Kudritzki and Hummer, 1990), non-LTE calculations of silicon, line strengths in B-type stars (Lennon et al., 1986), stellar opacity calculations and study (Iglesias et al., 1990; Iglesias and Rogers, 1992; Rogers and Iglesias, 1992; 1995; 1999; Seaton, 1993; Mostovych et al., 1995), atmospheres and winds of hot-star investigations (Butler, 1995) and investigation of Ga II lines in the spectrum of Ap stars (Lanz et al., 1993). Stark broadening data calculated within the MSE method were included in a critical overview of atomic data for stellar abundance analysis (Lanz and Artru, 1988), Stark broadening parameter regularities and systematic trends research (Glenzer et al., 1992; 1994; Wrubel et al., 1998; Purić et al., 1987, 1988a,b,c,d; Purić, 1996), etc. The MSE method was also employed in computer codes as, for example, the OPAL opacity code (Rogers and Iglesias, 1995), handbooks (Peach, 1996; Vogt, 1996) and monographs (Gray, 1992; Griem, 1997; Konjević, 1999). They also have been included by Golovatyj et al. (1997) in a catalogue of atomic data for low-density astrophysical plasmas.

8 APPLICATION TO THE INVESTIGATION OF ‘ZIRCONIUM CONFLICT’ IN THE χ LUPI STAR ATMOSPHERE

An example of the application of the MSE method is the study on the ‘zirconium conflict’ in the χ Lupi star atmosphere (Popović et al., 2001a). The electron-impact broadening is the main broadening mechanism in A- and B-type star atmospheres (see, for example, Popović et al., 1999). The electron-impact broadening data are needed for various problems in astrophysics, for example for diagnostic and modelling of stellar plasmas and the investigation of their physical properties and for abundance determination. These investigations provide us with useful information for modelling stellar evolution. As an example, the study of abundances in stellar atmospheres provides evidence for the chemical composition of the stellar primordial cloud, processes occurring within stellar interiors, and the dynamic processes in stellar atmospheres.

The available abundance analysis for early-type stars show that about 10–20% of A and B stars have abundance anomalies, including anomalies in isotopic compositions (Leckrone et al., 1993). The abundance anomalies in these stars, called CP stars, have been caused by different hydrodynamic processes in the outer stellar layers (aided and mitigated by magnetic fields, weak stellar winds, turbulence, rotation mixing, etc.). In order to investigate these processes, atomic data for numerous lines of numerous emitters are needed.

For example, zirconium lines are present in the spectra of Hg–Mn stars (Cowley and Aikman, 1975; Heacox, 1979; Leckrone et al., 1993; Sikström et al., 1999). It is interesting that the zirconium abundance determination from weak Zr II optical lines and strong Zr III lines (detected in the UV) is quite different (Leckrone et al., 1993; Sikström et al., 1999) in the Hg–Mn star χ Lupi. This is illustrated in Figure 3, where the UV spectrum of the χ Lupi star within the 193.83–193.87 nm wavelength range is shown. The solid curve is the spectrum obtained by GHRS. The dotted curve shows the synthesised Zr II 4d5s5p v $^2D^0_{3/2}$–$4d^2 5s$ a $^2D_{3/2}$ ($\lambda = 193.85$ nm) line obtained for the zirconium abundance $\log(N_{Zr}/N_H) = -8.12$. These abundance values are obtained from Zr III lines. The dashed curve is the synthesised spectrum for $\log(N_{Zr}/N_H) = -9.1$, and the curve with larger dots the spectrum for $\log(N_{Zr}/N_H) = -9.0$ (Leckrone et al., 1993).

This is the so-called 'zirconium conflict' and it was supposed by Sikström et al. (1999) that this difference is probably due to non-adequate use of stellar models, for example if the influence of non-LTE effects or if diffusion is not taken into account.

Zirconium, often overabundant in Hg–Mn stars (Heacox, 1979), is one member of the Sr–Y–Zr triad, which is vital for the study of s-process nucleosynthesis and has been indicated as presenting a non-nuclear abundance pattern in Hg–Mn stars. The most obvious interpretations of this anomaly are with the help of diffusion theory or with the inclusion of non-LTE effects. However, it is of interest also to investigate the contribution of the differences of Zr II and Zr III Stark broadening parameters to the zirconium conflict.

Popović et al. (2001a) performed a calculation of the electron-impact broadening parameters of two astrophysically important Zr II and 34 Zr III lines, in order to test the influence of this broadening mechanism on the determination of equivalent widths and to discuss its possible influence on zirconium abundance determination.

Atomic energy levels needed for calculations have been taken from the work of Reader and Acquista (1997) and from Charo et al. (1999). The results obtained have been used to see how much the electron-impact broadening can take part in so-called 'zirconium conflict' in the Hg–Mn star χ Lupi. In order to test the importance of the electron-impact broadening effect in the determination of zirconium abundance, Popović et al. (2001a) have synthesised the line profiles of Zr II ($\lambda = 193.8$ nm), and Zr III ($\lambda = 194.0$ nm) using the SYNTH code

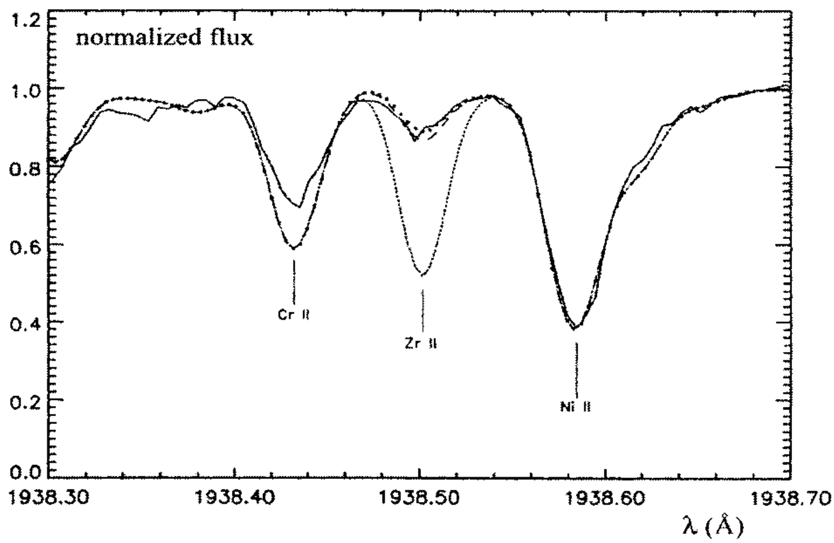

FIGURE 3 The UV spectrum of the χ Lupi star within the 193.83–193.87 nm wavelength range: ———, spectrum obtained by GHRS; ······, the synthesised Zr II 4d5s5p v $^2D^0_{3/2}$–$4d^2 5s$ a $^2D_{3/2}$ ($\lambda = 193.85$ nm) line obtained for $\log(N_{Zr}/N_H) = -8.12$ (these abundance values are obtained from Zr III lines); - - - - - -, synthesised spectrum for $\log(N_{Zr}/N_H) = -9.1$; •–•–•–, synthesised spectrum for $\log(N_{Zr}/N_H) = -9.0$ (Leckrone et al., 1993).

(Piskunov, 1992) and the ATLAS9 code for the stellar atmosphere model (Kurucz, 1993) $T_{eff} = 10{,}500\,K$, $\log g = 4.0$ and the turbulence velocity $V_t = 0.0\,km\,s^{-1}$; that is, with the stellar models with similar characteristics to χ Lupi ($T_{eff} = 10{,}650\,K$ and $\log g = 3.8$ (see, for example, Leckrone et al., 1999)). These lines have been chosen because they have usually been used for abundance determination. The reason is that the lines have small wavelength displacement and they are well resolved (Leckrone et al., 1993). The change in the Zr III $4d^2\ {}^3P_1$–$4d5p\ {}^3P^0_0$ ($\lambda = 193.725\,nm$) line profile due to the change in the zirconium abundance is shown in Figure 4(a), while in Figure 4(b), the equivalent width is shown as a function of the zirconium abundance.

Popović et al. (2001a) have calculated the equivalent widths with the electron-impact broadening effect and without it for different abundances of zirconium. The obtained results for Zr III (194.0 nm) and Zr II (193.8 nm) lines show that the electron broadening effect is more important in the case of higher zirconium abundances. The equivalent width increases with increasing abundance for both lines, but the equivalent width for the Zr III (194.0 nm) line is more sensitive than for the Zr II (193.8 nm) line. It may cause error in abundance determination in the case when the electron-impact broadening effect is not taken into account. In any case, synthesis of these two lines in order to measure the zirconium abundance without taking into account the electron-impact widths will show that with the Zr III (194.0 nm) the abundance of zirconium is higher than with the Zr II (193.8 nm) line. However, this effect cannot cause the difference of one order of magnitude in the abundance.

Although the ‘zirconium conflict’ in the Hg–Mn star χ Lupi cannot be explained only by this effect, one should take into account that this effect may cause errors in abundance determination. Moreover in Figure 5 it is demonstrated that Stark broadening is comparable with Doppler broadening or dominant broadening mechanisms for temperatures around 10,000 K and higher.

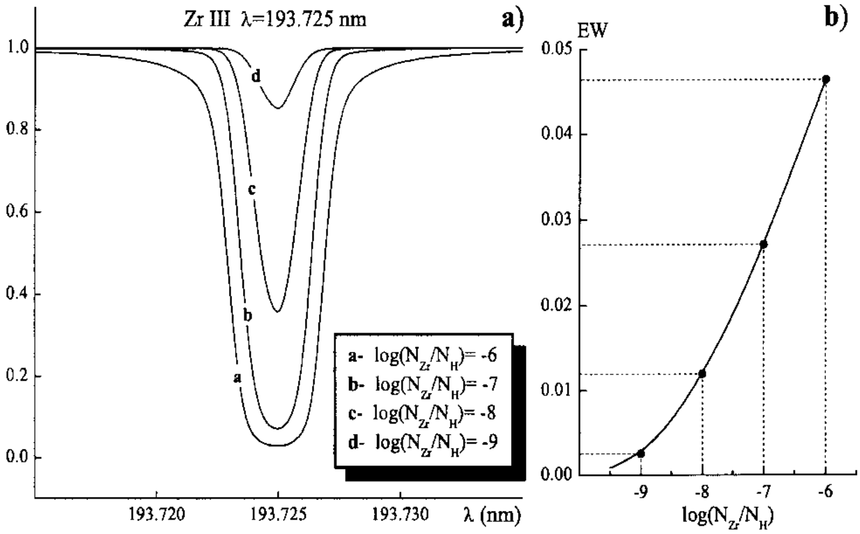

FIGURE 4 (a) The change in the Zr III $4d^2\ {}^3P_1$–$4d5p\ {}^3P^0_0$ ($\lambda = 193.725\,nm$) line profile due to the change in the zirconium abundance $\log(N_{Zr}/N_H)$ for the stellar atmosphere model with $T_{eff} = 10{,}500\,K$, $\log g = 4.0$ and the turbulence velocity $V_t = 0.0\,km\,s^{-1}$. (b) The equivalent width as a function of the zirconium abundance.

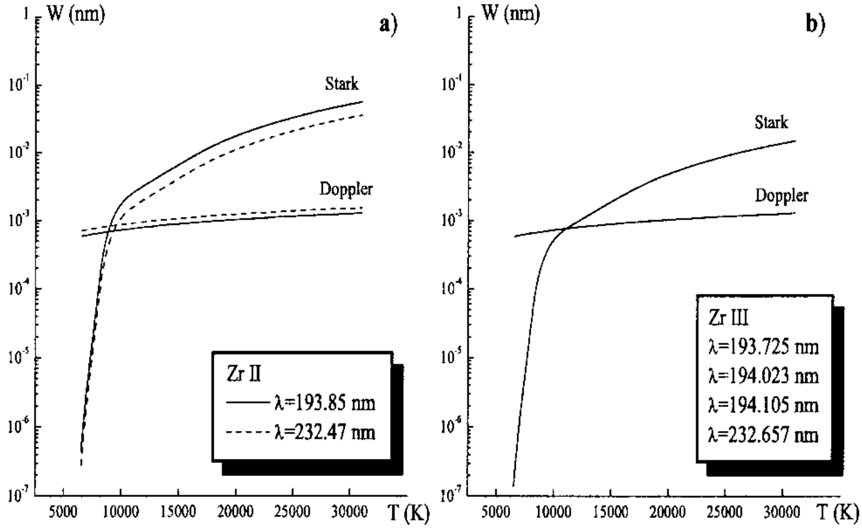

FIGURE 5 The behaviour of Stark and Doppler FWHMs with temperature, for the stellar atmosphere model with $T_{eff} = 10{,}500$ K, $\log g = 4.0$ and $V_t = 0.0\,\mathrm{km\,s^{-1}}$ for (a) Zr II 4d5s5p v $^2D^0_{3/2}$–4d^{2}5s a $^2D_{3/2}$ ($\lambda = 193.85$ nm) (———) and Zr II 4d5s5p v $^2F^0_{5/2}$–4d^{2}5s b $^2G_{7/2}$ ($\lambda = 232.47$ nm) (– – – –) and (b) Zr III 4d^2 $^3P_1$–4d5p $^3P^0_0$ ($\lambda = 193.725$ nm), Zr III 4d^2 $^1G_4$–4d5p $^1F^0_3$ ($\lambda = 194.023$ nm), Zr III 4d^2 $^3P_2$–4d5p $^3P^0_2$ ($\lambda = 194.105$ nm) and Zr III 4d^2 $^3P_1$–4d5p $^3P^0_1$ ($\lambda = 194.657$ nm). In (b) the dependences of all the indicated lines are not shown since they are approximately the same.

9 RARE-EARTH ELEMENTS IN CP STAR ATMOSPHERES

Another example of the applicability of the MSE method in astrophysics is the investigation of REE spectral lines in the spectra of CP stars. This is also an example of collaboration between the Belgrade Observatory and the Institute of Astronomy, Russian Academy of Sciences, through the project 'Collisional processes in stellar atmospheres' supported by the Serbian Academy of Sciences and Arts and the Russian Academy of Sciences, led by Luka Č. Popović from Serbia and Tanya A. Ryabchikova from Russia (see, for example, Popović et al., 1999).

Spectroscopic data for REEs are of interest for astrophysics since the lines of the ionised REEs are present in stellar spectra. Moreover, the REEs are overabundant in CP stars in a wide temperature domain (see, for example, Ryabchikova et al., 1999b), and the atomic data for REEs are needed in order to solve the astrophysical problems such as the relative abundances of r- and s-process elements in metal-poor halo stars and the evolution of CP stars (Cowley, 1984; Sneden et al., 1996). Usually, REE abundance analysis is based on the lines for the first ionisation stages, which have experimentally determined oscillator strengths. In some CP stars, for example HD 101065 (Cowley et al., 2000), very large excesses of REEs are presented. Popović et al. (1999) calculated the Stark widths and shifts for six Eu II lines and widths for three La II and six La III multiplets by using the MSE method. The influence of the electron-impact mechanism on line shapes and equivalent widths in hot-star atmospheres has been considered. It has been shown that Stark broadening is significant in hot stars, and it should be taken into account in the analysis of stellar spectral lines for $T_{eff} > 7000$ K, in particular if europium is overabundant.

Popović et al. (2001b) determined Stark broadening widths for 284 Nd II lines within the simplified MSE approach. The lines of Nd II are observed in the spectra of CP stars as well as in the spectra of other stars (see, for example, Guthrie, 1985; Adelman, 1987; Cowley et al., 2000). Owing to conditions in stellar atmospheres, the Nd II lines are dominant in comparison with Nd I and Nd III, lines; for example, in the spectra of HD 101065, a roAp star, Cowley et al. (2000) found 71 lines of Nd II and only six and seven lines of Nd I and Nd III, respectively. This is the reason why for determination of the neodymium abundance in the spectra of CP and other stars the Nd II lines are usually used. On the other hand, owing to the complexity of the Nd II spectrum, it is very difficult to obtain the atomic data (oscillator strengths, Stark widths, etc.) needed for astrophysical purposes. Popović et al. (2001) used for Stark width calculation the simplified MSE approach given by Dimitrijević and Konjević (1987). This formula gives better results than the older approximate formula given by Cowley (1971) often used for Stark width estimations when more sophisticated methods are not applicable.

In order to test the importance of the electron-impact broadening effect in stellar atmospheres, Popović et al. (2001b) have synthesised the line profiles of 38 Nd II lines using the SYNTH code (Piskunov, 1992) and the ATLAS9 code for stellar atmosphere models (Kurucz, 1993) in the temperature range of $6000\,\mathrm{K} \leq T_{\mathrm{eff}} \leq 16{,}000\,\mathrm{K}$ and $3.0 \leq \log g \leq 5.0$. They have synthesised the line profiles with and without taking into account the electron-impact broadening mechanism for different types of stellar atmosphere. Firstly, they synthesised all considered line profiles for neodymium abundance $A = \log([\mathrm{Nd}]/[\mathrm{H}]) = -7.0$, and two values of $\log g = 4.0$ and 4.5 for different effective temperatures ($T_{\mathrm{eff}} = 6000$–$16{,}000\,\mathrm{K}$). All considered lines have similar dependences on effective temperature. As an example in Figure 6, we show the ratio EW_{St}/EW_0 of the equivalent widths as a function of the stellar temperature for the Nd II (4013.3 Å) line. As one can see from Figure 6 the maximum of the electron-impact broadening influence on the equivalent widths is in the effective temperature range $T_{\mathrm{eff}} = 8000$–$10{,}000\,\mathrm{K}$. One should note here that the solar value for neodymium abundance is −10.55 which is three orders of magnitude lower than used in Figure 6, so that solar Nd II lines would be weak and relatively insensitive to the damping widths. Figure 7 illustrates the dependence of electron-impact

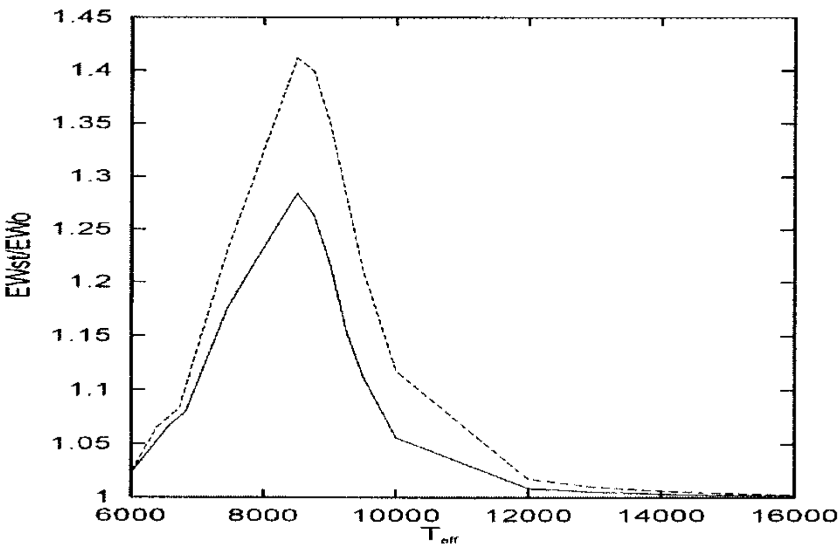

FIGURE 6 The ratio of equivalent widths for the Nd II (4013.3 Å) line calculated with Stark broadening effect (EW_{St}) and without it (EW_0) as a function of effective temperature: ———, results for $\log g = 4.0$; – – – –, results for $\log g = 4.5$.

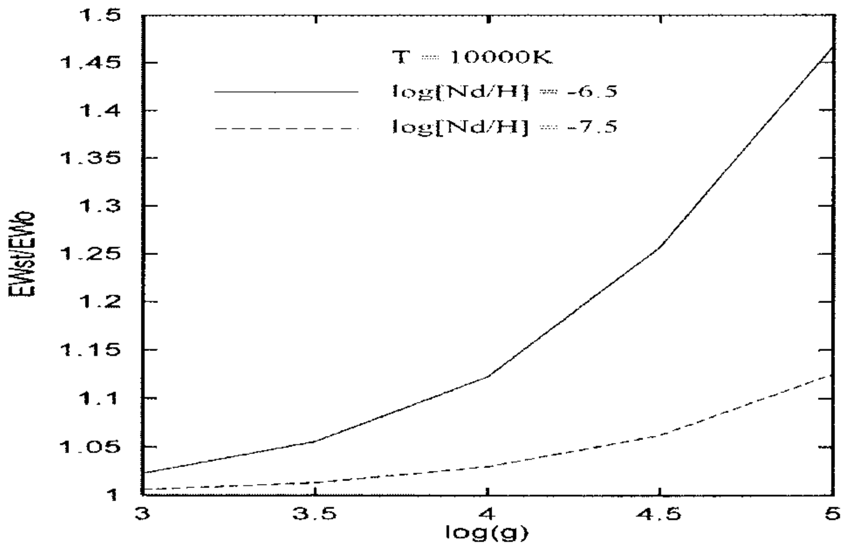

FIGURE 7 The ratio EW_{St}/EW_0 of the equivalent widths as a function of log g for the Nd II (4062.2 Å) line, for two abundances of neodymium.

broadening influence on the equivalent width versus surface gravity for the Nd II ($\lambda = 4062.2$ Å) line and log([Nd]/[H]) = −6.5 and −7.5. The influence is higher for higher neodymium abundances and increases with increase in surface gravity.

In order to point out the types of star where the electron-impact broadening effect is the most important, Popović et al. (2001b) summarised this influence in different types of stellar atmosphere, considering the minimal and maximal influence for all studied lines. The result is shown in Figure 8, where the equivalent widths ratio versus stellar spectral type is presented. As one can see from Figure 8, the most important influence of Stark broadening

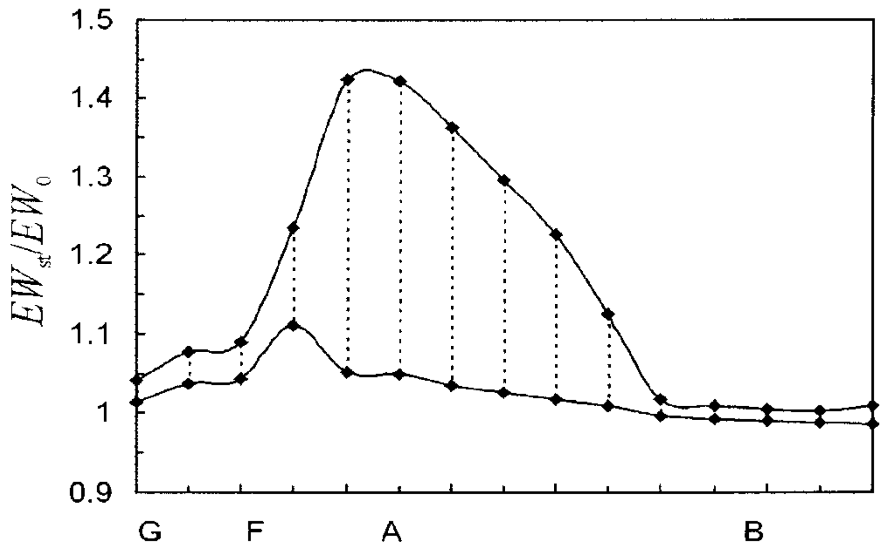

FIGURE 8 The maximal (upper curve) and minimal (lower curve) of the ratio EW_{St}/EW_0 of the equivalent widths for different types of star. The maximal and minimal value for all 38 Nd II considered lines are summarised.

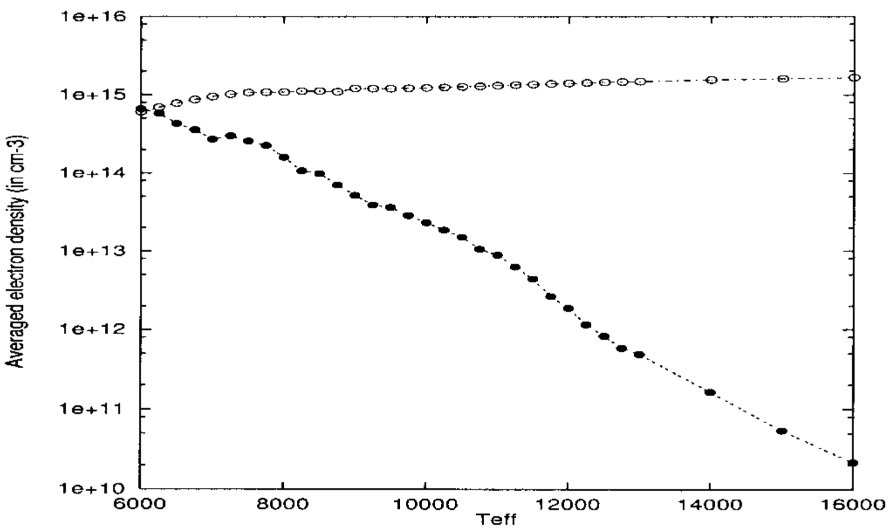

FIGURE 9 The averaged electron densities through all the atmosphere (○) and for layers where the neodymium ion density is maximal (T = 7000–9000 K) (●) as a function of the effective temperature corresponding to spectral types from G to B.

mechanism is in the A-type stellar atmospheres. Taking into account that Stark width depends on the electron density N, the effect is dominant in hot-star atmospheres where the electron density is higher, since hydrogen becomes ionised.

One can expect that the Stark broadening influence should be higher for hotter stars but, considering that the Nd II ion is created in a part of stellar atmosphere with corresponding plasma parameters, this is not the case. Starting from the fact that the ionisation potential of Nd II is 10.73 eV, consequently the layers where the Nd II ion density is maximal have electron temperature between 7000 and 9000 K, Popović et al. (2001b) have calculated the averaged electron density in these layers of stellar atmosphere for different stellar types for $\log g = 4.0$ and, as one can see in Figure 9, the averaged electron density decreases with increasing effective temperature. This is the reason why the maximal influence of the Stark broadening effect in the case of Nd II is in A-type stellar atmospheres.

10 DATABASE ‘BELDATA’

Another field which is a possibility for collaboration is the creation and development of databases. For example Luka Č. Popović as the Chairman of the Scientific Committee and Olga B. Dluzhnevskaya, Miltcho Tsvetkov and Milan S. Dimitrijević, organised within the 12th National Conference of Yugoslav Astronomers held in Belgrade on November 19–21, 1999) International Workshop on the Development of Astronomical Databases.

There are several approaches to collecting useful data which might be organised in databases.

(i) First of all one can collect the references or the references with citations, which may be published as a book but also organised as a database, for example the Science Citation Index or the Astrophysical Data System.

(ii) Data can be collected from literature or other sources, for example Stark broadening data obtained by the Astronomical Observatory, Belgrade.

(iii) A critically evaluated set of data is particularly useful, for example critically evaluated Stark broadening data published by Nikola Konjević and his co-workers (see, for example, Konjević et al., 2002 and references therein).
(iv) In astronomy, a large amount of observational data is published in different stellar catalogues. Such catalogues are published by the Astronomical Observatory, Belgrade, by Sofija Sadžakov, Miodrag Dačić, Zorica Cvetković, Georgije Popović, etc., and our intention is to organize them in the future as a database.
(v) At the Astronomical Observatory, Belgrade, and other old observatories, a large amount of photographic plates with observational data are stored. An international effort is being made to digitalise such data and to organise them as databases available to the international scientific community.
(vi) Journals and publications may also be put in a database, enabling a search to be made through key words.

The project of the realisation of the database 'BelData' of the Astronomical Observatory, Belgrade, includes the creation and development of the database for the following: Stark broadening parameters obtained mainly by fellows of the group of astrophysical spectroscopy and their co-workers; spectra of active galaxies, observed or reduced by the staff of the Astronomical Observatory, Belgrade; stellar catalogues observed and deduced in Belgrade; abstracts of papers (and later full papers) appearing in Publications of the Astronomical Observatory, Belgrade.

The first phase of the design and elaboration of the astronomical database BelData is finished. Database serving as the web interface support has been designed and finished, as well as the web interface for data access and the corresponding search. Also a designed and elaborated database for Stark broadening parameters (linewidths and shifts) was obtained using semiclassical perturbation formalism. In fact the database contains catalogues of data for Be I, Sr I, Be III, B III, O IV, P IV, C V, O V, P V, S V, Ne VIII, Ca IX, Ca X, Al XI, Si XI, Si XII and Si XIII. Relational databases have been realised using the MySQL server. A web interface has been realised in PHP, Java Script and HTML. The internet address of the 'BelData' database is http://www.aob.bg.ac.yu/BELDATA.

We have also developed a collaboration with the following databases:

(i) database of the Institute of Astronomy, Russian Academy of Sciences, Moscow (http://www.inasan.rssi.ru), supervised by Olga B. Dluzhnevskaya;
(ii) wide field photographic observations database (http://skyarchive.org), created in Sofia by Milcho Tsvetkov and his co-workers; an agreement on cooperation in the digitalisation and organisation in a database of old photographic plates on Belgrade Astronomical Observatory is in preparation;
(iii) Astrophysical data system (http://adswww.harvard.edu/BOBeo) where the Serbian Astronomical Journal is available;
(iv) VALD2 database from the Vienna Observatory; Professor Werner Weiss provided help in the database creation for Nenad Milovanović and we coordinated the database organisation so that the two databases will be complementary.

All the above-mentioned work on the creation and development of BelData is advancing very slowly because of financial difficulties but we hope that the development of such databases will be useful for the scientific community.

11 OTHER EXAMPLES OF THE APPLICATIONS OF THE BELGRADE SCHOOL'S STARK BROADENING RESULTS

As other examples of applications of the Belgrade school's Stark broadening results, it should be noted that a simplified semiclassical formula for the Stark broadening of isolated neutral atom lines developed by Dimitrijević and Konjević (1986) has been applied by Leushin et al. (2000) for investigation of helium abundance in atmospheres of helium-rich stars and that results of Vince and Dimitrijević (1989) on the influence of pressure broadening on solar line bisectors has been applied by Atroshenko et al. (1990) for the examination of the fine structure of Fraunhofer lines.

Finally the following collaborations should be mentioned: with Popović et al. (1998) on the investigation of long-term Hβ line profile variation in Akn 120; with Vince et al. (2000) on the analysis of observed Mn I ($\lambda = 539.47$ nm) line profiles in solar plates; with Dimitrijević and Min'ko (1996) on the investigation of the actual state in theory and experiment in Stark broadening; with Salakhov, Sarandaev and Il'in on the investigation of Stark broadening of spectral lines of neutral copper (Dimitrijević et al., 1996).

Finally one should note that Belorussian and Serbian physicists and astronomers organised four Yugoslav–Belorussian and Belorussian–Yugoslav Symposia on the Physics and Diagnostics of Laboratory and Astrophysical Plasmas (held in Minsk in 1996, in Zlatibor in 1998, in Minsk in 2000 and in Belgrade in 2002), which have been published in the Publications of the Astronomical Observatory, Belgrade.

Acknowledgement

This work is a part of the project 'Influence of collisional processes on astrophysical plasma line shapes', supported by the Ministry of Science, Technologies and Development of Serbia.

References

Adelman, S. J. (1987) In: Adelman, S. J. and Lanz, T. (Eds.), Elemental Abundance Analyses, Proceedings of the IAU Working Group on Ap Stars Workshop. Institut d'Astronomie, l'Université de Lausanne, Lausanne, p. 58.

Alecian, G., Michaud, G. and Tully, J. (1993) Astrophys. J. 411, 882.

Andrievsky, S. M., Korotin, S. A., Luck, R. E. and Kostynchuk, L. Yu. (1999) Astron. Astrophys. 350, 598.

Atroshchenko, I. N., Gadun, A. S. and Kostyk, R. I. (1990) Kinematika Fiz. Nebesnykh Tel 6, 3.

Bassalo, J. M., Cattani, M. and Walder, V. S. (1982) J. Quant. Spectrosc. Radiat. Transfer 28, 75.

Bayazitov, U. Sh. and Saghidulin, I. Kh. (1996) Proceedings of the 10th General Conference of the European Physical Society, Trends in Physics, European Physical Society, Sevilla, Spain, p. 289.

Beauchamp, A., Wesemael, F. and Bergeron, P. (1997) Astrophys. J., Suppl. Ser. 108, 559.

Benett, S. M. and Griem, H. R. (1971) Technical Report 71-097, University of Maryland, College Park, Maryland, USA.

Bikmaev, I. F., Ryabchikova, T. A., Bruntt, H., Musaev, F. A., Mashonkina, L. I., Belyakova, E. V., Shimansky, V. V., Barklem, P. S. and Galazutdinov, G. (2002) Astron. Astrophys. 389, 537.

Bolcal, C., Kocer, D. and Adelman, S. J. (1992) Mon. Not. R. Astron. Soc. 258, 270.

Brandt, J. C., Heap, S. R., Beaver, E. A., Boggess, A., Carpenter, K. G., Ebberts, D. C., Hutchings, J. B., Jura, M., Leckrone, D. S., Linsky, J. L., Haran, S. P., Savage, B. D., Smith, A. M., Trafton, L. M., Walter, F. M., Weymann, R. J., Proffitt, C. R., Wahlgren, G. M., Johansson, S. G., Nilsson, H., Brage, T., Snow, M. and Ake, T. B. (1999) Astron. J. 117, 1505.

Butler, K. (1995) In: Adelman, S. J. and Wiese, W. L. (Eds.), Astrophysical Applications of Powerful New Databases, ASP Conference Series, Vol. 78, Astronomical Society of the Pacific, San Francisco, p. 509.

Charo, E., López-Ayuso, J. L. and Martin, I. (1999) J. Phys. B 32, 4555.

Chayer, P., Fontaine, G. and Wesemael, F. (1995a) Astrophys. J., Suppl. Ser. 99, 189.

Chayer, P., Vennes, S., Pradhan, A. K., Thejll, P., Beauchamp, A., Fontaine, G. and Wesemael, F. (1995b) Astrophys. J. 454, 429.

Cowley, C. R. (1971) Observatory 91, 139.

Cowley, C. R. (1984) Phys. Scripta T 8, 28.

Cowley, C. R. and Aikman, G. C. L. (1975) Astrophys. J. 196, 521.
Cowley, C. R. and Greensberg, M. (1988) Mon. Not. R. Astron. Soc. 232, 763.
Cowley, C. R., Ryabchikova, T., Kupka, F., Bord, D. J., Mathys, G. and Bidelman, W. P. (2000) Mon. Not. R. Astron. Soc. 317, 299.
Dimitrijević, M. S. (1983) Astron. Astrophys. 127, 68.
Dimitrijević, M. S. (1990a) In: Wehrse, R. (Ed.), Accuracy of Element Abundances from Stellar Atmospheres, Lecture Notes in Physics, Vol. 356. Springer, Berlin, p. 31.
Dimitrijević, M. S. (1990b) Publs Astron. Obs., Belgrade 39.
Dimitrijević, M. S. (1991) Publs Astron. Obs., Belgrade 41.
Dimitrijević, M. S. (1994) Publs Astron. Obs., Belgrade 47.
Dimitrijević, M. S. (1996) Zh. Prikl. Spektrosk. 63, 810.
Dimitrijević, M. S. (1997a) Publs Astron. Obs., Belgrade 58.
Dimitrijević, M. S. (1997b) Astrophys. Space Sci. 252, 415.
Dimitrijević, M. S. (2001) Publs Astron. Obs., Belgrade 70.
Dimitrijević, M. S. and Artru, M.-C. (1986) Proceedings of the 13th Symposium on the Physics of Ionized Gases, Šibenik, 1986, Dept. of Physics and Meteorology, University of Belgrade, Belgrade, p. 317.
Dimitrijević, M. S., Feautrier, N. and Sahal-Bréchot, S. (1981) J. Phys. B 14, 2559.
Dimitrijević, M. S., Il'in, G. G., Sarandaev, E. V. and Salakhov, M. Kh. (1996) Proceedings of the 18th Symposium on the Physics of Ionized Gases, Kotor, 1996, Faculty of Sciences, Institute of Physics, Novisad, p. 283.
Dimitrijević, M. S. and Konjević, N. (1980) J. Quant. Spectrosc. Radiat. Transfer 24, 451.
Dimitrijević, M. S. and Konjević, N. (1981) In: Wende, B. (Ed.), Spectral Line Shapes. W. de Gruyter, Berlin, p. 211.
Dimitrijević, M. S. and Konjević, N. (1986) Astron. Astrophys. 163, 297.
Dimitrijević, M. S. and Konjević, N. (1987) Astron. Astrophys. 172, 345.
Dimitrijević, M. S. and Kršljanin, V. (1986) Astron. Astrophys. 165, 269.
Dimitrijević, M. S. and Min'ko, L. Ya. (1996) Publs Astron. Obs., Belgrade 53, 19.
Dimitrijević, M. S. and Popović, L. Č. (1993) Astron. Astrophys., Suppl. Series 101, 583.
Dimitrijević, M. S. and Popović, L. Č. (2001) Zh. Prikl. Spektrosk. 68, 685.
Dimitrijević, M. S., Ryabchikova, T., Popović, L. Č., Shulyak, D. and Tsymbal, V. (2003) Astron. Astrophys. (in press).
Dimitrijević, M. S. and Sahal-Bréchot, S. (1984a) J. Quant. Spectrosc. Radiat. Transfer 31, 301.
Dimitrijević, M. S. and Sahal-Bréchot, S. (1984b) Astron. Astrophys. 136, 289.
Dimitrijević, M. S. and Sahal-Bréchot, S. (1985a) J. Quant. Spectrosc. Radiat. Transfer 34, 34.
Dimitrijević, M. S. and Sahal-Bréchot, S. (1985b) Phys. Rev. A 31, 316.
Dimitrijević, M. S. and Sahal-Bréchot, S. (1989) Bull. Obs. Astron., Belgrade 141, 57.
Dimitrijević, M. S. and Sahal-Bréchot, S. (1990) Astron. Astrophys., Suppl. Ser. 82, 519.
Dimitrijević, M. S. and Sahal-Bréchot, S. (1991) Astron. Astrophys., Suppl. Ser. 82, 519.
Dimitrijević, M. S. and Sahal-Bréchot, S. (1993) J. Quant. Spectrosc. Radiat. Transfer 49, 157.
Dimitrijević, M. S. and Sahal-Bréchot, S. (1994) Bull. Astron., Belgrade 149, 31.
Dimitrijević, M. S. and Sahal-Bréchot, S. (1995a) Bull. Astron., Belgrade 151, 101.
Dimitrijević, M. S. and Sahal-Bréchot, S. (1995b) Physica Scripta 52, 41.
Dimitrijević, M. S. and Sahal-Bréchot, S. (1996) Physica Scripta 54, 50.
Dimitrijević, M. S., Sahal-Bréchot, S. and Bommier, V. (1991a) Astron. Astrophys., Suppl. Ser. 89, 581.
Dimitrijević, M. S., Sahal-Bréchot, S. and Bommier, V. (1991b) Astron. Astrophys., Suppl. Ser. 89, 591.
Feldman, U. and Doschek, G. A. (1977) Astrophys. J. 212, 913.
Fleurier, C., Sahal-Bréchot, S. and Chapelle, J. (1977) J. Quant. Spectrosc. Radiat. Transfer 17, 595.
Gies, D. R. and Lambert, D. L. (1992) Astrophys. J. 387, 673.
Glagolevskij, Yu. V. and North, P. (2000) In: Glagolevskij, Yu. V. and Romanyuk, I. I. (Eds.), Magnetic Fields of Chemically Peculiar and Related Stars. Special Astrophysical Observatory, Russian Academy of Sciences, Moscow, p. 173.
Glenzer, S., Uzelac, N. I., Kunze, H.-J. (1992) Phys. Rev. A. 45, 8795
Glenzer, S., Hey, J. D., Kunze, H.-J. (1994) J. Phys. B. 27, 413
Golovatyj, V. V., Sapar, A., Feklistova, T. and Kholtygin, A. F. (1997) Astron. Astrophys. Trans. 12, 85.
Gonzales, J. F., Artru, M.-C. and Michaud, G. (1995a) Astron. Astrophys. 302, 788.
Gonzales, J. F., LeBlanc, F., Artru, M.-C. and Michaud, G. (1995b) Astron. Astrophys. 297, 223.
Gonzales-Delgado, R. M., Leitherer, C. and Heckman, T. M. (1999) Astrophys. J., Suppl. Ser. 125, 489.
Gray, D. F. (1992) The Observation and Analysis of Stellar Photospheres. Cambridge University Press, Cambridge.
Griem, H. R. (1968) Phys. Rev. 165, 258.
Griem, H. R. (1974) Spectral Line Broadening by Plasmas. Academic Press, New York.
Griem, H. R. (1997) Principles of Plasma Spectroscopy, Cambridge Monographs of Plasma Physics, Vol. 2. Cambridge University Press, Cambridge.
Griem, H. R., Blaha, M. and Kepple, P. C. (1979) Phys. Rev. A 19, 2421.
Guthrie, B. N. G. (1985) Mon. Not. R. Astron. Soc. 216, 15.
Hauschildt, P. H. and Baron, E. (1999) J. Comput. Appl. Math. 109, 41.
Heacox, W. D. (1979) Astrophys. J., Suppl. Ser. 41, 675.
Iglesias, C. A., Rogers, F. J. and Wilson, B. G. (1990) Astrophys. J. 360, 221.
Iglesias, C. A. and Rogers, F. J. (1992) Revta Mex. Astron. Astrofis. 23, 161.

Israelian, G., Friedjung, M., Graham, J., Muratoio, G., Rossi, C. and de Winter, D. (1996) Astron. Astrophys. 311, 643.
Johansson, S. (1988) In: Viotti, R., Vitone, A. and Friedjung, M. (Eds.), Physics of Formation of Fe II Lines Outside LTE. Reidel, Dordrecht, p. 13.
Jones, W. W., Benett, S. M. and Griem, H. R. (1971) Technical Report 71-128, University of Maryland, College Park, Maryland, USA.
Khokhlova, V. L. (1994) Pis'ma Astron. Zh. 20, 110.
Konjević, N. (1999) Phys. Rep. 316, 339.
Konjević, N., Lesage., A, Fuhr, J. R. and Wiese, W. L. (2002) J. Phys. Chem. Ref. Data 31, 819.
Kopylov, I. M., Leushin, V. V., Topil'skaya, G. P., Tsymbal, V. V. and Gvozd', Yu. A. (1989) Izv. Spec. Astrophys. Obs., Russ. Acad. Sci. 28, 72.
Korotin, S. A., Andrievsky, S. M. and Luck, R. E. (1999) Astron. Astrophys. 351, 168.
Kuschnig, R., Ryabchikova, T., Piskunov, N., Weiss, W. W. and LeContel, J. M. (1995) Astron. Astrophys. 294, 757.
Kudritzki, R. and Hummer, D. G. (1990) A. Rev. Astron. Astrophys. 28, 303.
Kurucz, R. L. (1993) Model atmosphere program ATLAS9, CDROM13.
Kurucz, R. L., Furenlid, I., Brault, J. and Testerman, L. (1984) NSO Atlas No. 1: Solar Flux Atlas from 296 to 1300 nm, National Solar Observatory, Sacramento Peak, Sunspot, New Mexico.
Lanz, T. and Artru, M.-C. (1988) In: Adelman, S. J. and Lanz, T. (Eds.), Elemental Abundance Analysis. Institut d'Astronomie, l'Université de Lausanne, Lausanne, p. 156.
Lanz, T., Artru, M.-C., Didelon, P. and Mathys, G. (1993) Astron. Astrophys. 272, 465.
Lanz, T., Dimitrijević, M. S. and Artru, M.-C. (1988) Astron. Astrophys. 192, 249.
LeBlanc, F. and Michaud, G. (1995) Astron. Astrophys. 303, 166.
Leckrone, D. S., Proffitt, C. R., Wahlgren, G. M., Johansson, S. G. and Brage, T. (1999) Astron. J. 117, 1454L.
Leckrone, D. S., Wahlgren, G. M., Johansson, S. G. and Adelman, S. J. (1993) In: Dworetsky, M. M., Castelli, F. and Faraggiana, R. (Eds.), Peculiar Versus Normal Phenomena in A-Type and Related Stars, ASP Conference Series, Vol. 44, p. 42.
Lennon, D. J., Lynas-Gray, A. E., Brown, J. F. and Dufton, P. L. (1986) Mon. Not. R. Astron. Soc. 222, 719.
Leushin, V. V., Glagolevskij, Yu. V. and North, P. (2000) In: Glagolevskij, Yu. V. and Romanyuk, I. I. (Eds.), Magnetic Fields of Chemically Peculiar and Related Stars, Special Astrophysical Observatory. Russian Academy of Sciences, Moscow, p. 173.
Madej, J. (1989) Astron. Astrophys. 209, 226.
Mazing, M. A., Marinković, M. D. and Vrublevskaya, N. A. (1964) Bull. 'Boris Kidrič' Inst. Nucl. Sci. 15, 15.
Michaud, G. and Richer, J. (1992) In: Zoppi, M. and Ulivi, L. (Eds.), Spectral Line Shapes, Vol. 9, Proceedings, Vol. 386. American Institute of Physics, New York, p. 397.
Mostovych, A. N., Chan, L. Y., Kearney, K. J., Garren, D., Iglesias, C. A., Klapisch, M. and Rogers, F. J. (1995) Phys. Rev. Lett. 75, 1530.
Omont, A. and Encrenaz, P. (1977) Astron. Astrophys. 56, 447.
Paerels, F. (1997) Astrophys. J. 476, L47.
Peach, G. (1996) In: Drake, G. W. F. (Ed.), Atomic, Molecular, and Optical Physics Handbook. American Institute of Physics, Woodbury, New York, p. 669.
Piskunov, N. E. (1992) In: Glagolevskij, Yu. V. and Romanyuk, I. I. (Eds.), Stellar Magnetism. Nauka, St Petersburg, p. 92.
Piskunov, N. E. and Kupka, F. (2001) Astrophys. J. 547, 1040.
Piskunov, N. E., Kupka, F., Ryabchikova, T. A., Weiss, W. W. and Jeffery, C. S. (1995) Astron. Astrophys. Suppl. Ser. 112, 525.
Piskunov, N. E., Ryabchikova, T. A., Kuschnig, R. and Weiss, W. W. (1994) Astron. Astrophys. 291, 910.
Popović, L. Č. and Dimitrijević, M. S. (1996a) Physica Scripta 53, 325.
Popović, L. Č. and Dimitrijević, M. S. (1996b) Astron. Astrophys., Suppl. Ser. 116, 359.
Popović, L. Č. and Dimitrijević, M. S. (1998) Astron. Astrophys., Suppl. Ser. 127, 259.
Popović, L. Č., Dimitrijević, M. S. and Ryabchikova, T. (1999) Astron. Astrophys. 350, 719.
Popović, L. Č., Milovanović, N. and Dimitrijević, M. S. (2001a) Astron. Astrophys. 365, 656.
Popović, L. Č., Simić, S., Milovanović, N. and Dimitrijević, M. S. (2001b) Astrophys. J., Suppl. Ser. 135, 109.
Popović, L. Č., Trajković, N., Kubičela, A., Doroshenko, V. T., Sergeev, S. G., Bon, E. and Stanić, I. (1998) Publs Astron. Obs., Belgrade 61, 139.
Purić, J. (1996) Zh. Prikl. Spektrosk. 63, 816.
Purić, J., Srećković, A., Djeniže, S. and Platiša, M. (1987) Phys. Rev. A 36, 3957
Purić, J., Djeniže, S., Srećković, A. and Ćuk, M. (1988a) Fizika 20, 485.
Purić, J., Djeniže, S., Srećković, A., Ćuk, M., Labat, J., Platiša, M. (1988b) Z. Phys. D 8, 348.
Purić, J., Djeniže, S., Srećković, A., Platiša, M. and Labat, J. (1988c) Phys. Rev. A 37, 498.
Purić, L. J., Djeniže, S., Labat, J., Platiśa, M., Srećković, A. and Ćuk, M. (1988d) Z. Phys. D 10, 431.
Reader, J. and Acquista, N. (1997) Physica Scripta 55, 310.
Rogers, F. J. and Iglesias, C. A. (1992) Astrophys. J., Suppl. Ser. 79, 507.
Rogers, F. J. and Iglesias, C. A. (1995) In: Adelman, S. J. and Wiese, W. L. (Eds.), Astrophysical Applications of Powerful Databases, ASP Conference Series, Vol. 78, Astronomical Society of the Pacific, San Francisco, p. 31.
Rogers, F. J. and Iglesias, C. A. (1999) Space Sci. Rev. 85, 61.
Russel, H. N. (1926) Astrophys. J. 64, 194.

Ryabchikova, T. A., Malanushenko, V. P. and Adelman, S. J. (1999a) Astron. Astrophys. 351, 963.
Ryabchikova, T. A., Piskunov, N., Savanov, I., Kupka, F. and Malanushenko, V. (1999b) Astron. Astrophys. 343, 229.
Ryabchikova, T. A., Savanov, I. S., Hatzes, A. P., Weiss, W. W. and Handler, G. (2000) Astron. Astrophys. 357, 981.
Ryabchikova, T. A. and Smirnov, Yu. M. (1994) Astron. Zh. 71, 83.
Sahal-Bréchot, S. I. (1969a) Astron. Astrophys. 1, 91.
Sahal-Bréchot, S. I. (1969b) Astron. Astrophys. 2, 322.
Sahibullin, N. A. and Shabert, V. Ya. (1990) Pis'ma Astron. Zh. 16, 539.
Schmidt, G. D., West, S. C., Liebert, J., Green, R. F. and Stockman, H. S. (1986) Astrophys. J. 309, 218.
Seaton, M. J. (1993) Publs Astron. Soc. Pacif. 40, 222.
Seaton, M. J. (1997) Mon. Not. R. Astron. Soc. 289, 700.
Sikström, C. M., Lundberg, H., Wahlgren, G. M., Li, Z. S., Lyngå, C., Johansson, S. and Lecrone, D. S. (1999) Astron. Astrophys. 343, 297.
Smirnov, G. T., Sorochenko, R. L. and Pankonin, V. (1984) Astron. Astrophys. 135, 116.
Smith, K. C. (1993) Astron. Astrophys. 276, 393.
Sneden, C., McWilliam, A., Preston, G. W., Cowan, J. J., Burris, D. L. and Armosky, B. J. (1996) Astrophys. J. 467, 819.
Stehlé, C. (1994) Astron. Astrophys., Suppl. Ser. 104, 509.
Stehlé, C. (1995) In: May, A. D., Drummond, J. R. and Oks, E. (Eds.), Spectral Line Shapes, Vol. 8, AIP Conference Proceedings, Vol. 328. American Institute of Physics, New York, p. 36.
Topilskaya, G. P. (1993) Astrofiz. Issled. 36, 52.
Tsymbal, V. V. (1991) Astrofiz. Issled. 34, 113.
Tsymbal, V. V. (1996) In: Adelman, S. J., Kupka, F. and Weiss, W. W. (Eds.), Model Atmospheres and Spectral Synthesis, ASP Conference Series, Vol. 108, Astronomical Society of the Pacific, San Francisco, p. 198.
Valenti, J. A. and Piskunov, N. (1996) Astron. Astrophys. Suppl. Ser. 118, 595.
Vince, I. and Dimitrijević, M. S. (1985) Publs Astron. Obs., Belgrade 33, 15.
Vince, I. and Dimitrijević, M. S. (1989) In: Rutten, R. J. and Severino, G. (Eds.), Solar and Stellar Granulation. Kluwer, Dordrecht, p. 93.
Vince, I., Dimitrijević, M. S. and Kršljanin, V. (1985a) In: Rostas, F. (Ed.), Spectral Line Shapes III. W. de Gruyter, Berlin, p. 649.
Vince, I., Dimitrijević, M. S. and Kršljanin, V. (1985b) In: Beckman, J. and Crivelari, L. (Eds.), Progress in Stellar Spectral Line Formation Theory. Reidel, Dordrecht, p. 373.
Vince, I., Gopasyuk, O., Gopasyuk, S. and Vince, O. (2000) Proceedings of the 20th Symposium on the Physics of Ionized Gases, Zlatibor, 2000, Institute of Physics, Faculty of Physics, University of Belgrade, Institute of Nuclear Sciences "Vinčá", Belgrade, p. 507.
Vogt, H. H. (Ed.) (1996) Stellar Atmospheres: Atomic and Molecular Data, Astronomy and Astrophysics, Extension and Suppl. to Vol. 2, Subvol. B, Stars and Star Clusters, Landolt–Börnstein, Group VI, Vol. 3. Springer, Berlin, p. 57.
Vogt, S. S., Penrod, I. G. D. and Hatzes, A. P. (1987) Astrophys. J. 321, 469.
Werner, K., Heber, U. and Hunger, R. (1991) Astron. Astrophys. 244, 437.
Wrubel, T., Ahmad, I., Buscher, S. and Kunze, H.-J. (1998) Phys. Rev. E 57, 5972.
Zaharova, L. A. (1994) Astron. Zh. 71, 588.
Zaharova, L. A. and Ryabchikova, T. A. (1996) Pis'ma Astron. Zh. 22, 172.
Zboril, M., North, P., Glagolevskij, Y. V. and Betrix, F. (1997) Astron. Astrophys. 324, 949.