Atoms **2014**, *2*, 357-377; doi:10.3390/atoms2030357

OPEN ACCESS

atoms

ISSN 2218-2004
www.mdpi.com/journal/atoms

Article

On the Application of Stark Broadening Data Determined with a Semiclassical Perturbation Approach

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Received: 5 May 2014; in revised form: 20 June 2014 / Accepted: 16 July 2014 /
Published: 7 August 2014

Abstract: The significance of Stark broadening data for problems in astrophysics, physics, as well as for technological plasmas is discussed and applications of Stark broadening parameters calculated using a semiclassical perturbation method are analyzed.

Keywords: Stark broadening; isolated lines; impact approximation

1. Introduction

Stark broadening parameters of neutral atom and ion lines are of interest for a number of problems in astrophysical, laboratory, laser produced, fusion or technological plasma investigations. Especially the development of space astronomy has enabled the collection of a huge amount of spectroscopic data of all kinds of celestial objects within various spectral ranges. Consequently, the atomic data for trace elements, which had not been of interest in astrophysics before, have become more and more important, and, since we do not know *a priori* the chemical composition of a star, the interest for a very extensive list of such data, as well as for the corresponding databases has been increasing, stimulating the theoretical and experimental work on spectral lineshape research.Such data are particularly needed for interpretation, synthesis and analysis of high resolution spectra with well-resolved line profiles, obtained from space born instruments in space missions like the Far Ultraviolet

Spectroscopy Explorer (FUSE), the Goddard High Resolution Spectrograph (GHRS—the Hubble Space Telescope), the International Ultraviolet Explorer and many others. Space high resolution spectroscopy has demonstrated that ionized manganese, tellurium, gold, indium, tin, chromium, ruthenium, zinc, copper, selenium, rare earths and other trace elements, which prior to the epoch of space born stellar spectroscopy had been completely insignificant for astrophysics, are present in hot stellar atmospheres, where Stark broadening is particularly significant.

In comparison with laboratory plasmas, conditions in astrophysical plasmas, where the Stark broadening mechanism is important, are incomparably more various. This broadening mechanism is of interest for astrophysical plasmas with such extreme conditions like for example the plasma in interstellar molecular clouds, with typical electron temperatures around 30 K or smaller, and typical electron densities of several electrons per cubic centimeter. In plasma of such low density, free electrons may be recombined in a very distant orbit with very large principal quantum number values of several hundreds and deexcited in cascade radiating in the radio domain. Since such distant electrons are weakly bounded with the core, even very weak electric microfields can have a significant influence.

Hydrogen, which is usually the main constituent of stellar atmospheres for temperatures larger or near 10,000 K is ionized in such amount that Stark broadening is the dominant collisional broadening mechanism for spectral lines. This is the case for white dwarfs and hot stars of the O, B and A type. Even for lower temperatures and for cooler stars of the solar type, Stark broadening may be important for spectral lines originating from highly excited atoms, where the distant, weakly bounded, optical electron is significantly influenced by weak electric microfields. This broadening mechanism is also important even for cooler stars for the investigation and modeling of subphotospheric layers.

In the above mentioned cases, when Stark broadening is of interest, the corresponding line broadening parameters (line widths and shifts) are significant e.g. for interpretation, synthesis and analysis of stellar spectral lines, determination of chemical abundances of elements from equivalent widths of absorption lines, estimation of the radiative transfer through the stellar atmospheres and subphotospheric layers, opacity calculations, radiative acceleration considerations, nucleosynthesis research and other astrophysical topics. Stark broadening is of interest for the investigation of neutron stars. The electron densities and temperatures in atmospheres of such stars are orders of magnitude larger than in atmospheres of white dwarfs and are typical for stellar interiors. Temperatures in the extremely thin atmospheric layer where the photospheric emission originates are of the order of 10^6–10^7 K and electron densities of the order of 10^{24} cm^{-3}, which are plasma conditions where Stark broadening dominates.

Stark broadening data are also of interest for laboratory plasma diagnostics, laser produced plasma investigation and modeling, the design of laser devices, inertial fusion plasma and for analysis and modeling of various plasmas in technology, as for example for laser welding and piercing and for plasmas in light sources.

The most sophisticated theoretical method for the calculation of a Stark broadened line profile is the quantum mechanical strong coupling approach, but due to its complexity and numerical difficulties, it is not adequate for large scale determination of Stark broadening parameters, in particular for e.g., complex spectra, heavy elements or transitions between highly excited energy levels. Consequently, in a lot of cases, the semiclassical approach remains the most efficient method for Stark broadening calculations, which has provided the largest set of existing theoretical results.

In order to complete as much as possible the Stark broadening data important for various topics in astrophysics, physics and technology, Stark broadening parameters for a number of spectral lines of various emitters have been determined in a series of papers, using the semiclassical perturbation formalism [1,2]. The corresponding computer code was innovated and optimized several times (see the article Sahal-Bréchot *et al.* in this issue). Up to now, Stark broadening parameters (line widths and shifts) for spectral lines or multiplets of the following atoms and ions have been calculated and published: He I, Li I, Li II, Be I, Be II, Be III, B II, B III, C II, C III, C IV, C V, N I, N II, N III, N IV, N V, O I, O II, O III, O IV, O V, OVI, OVII, F I, F II, F III, F V, F VI, F VII, Ne I, Ne II, Ne III, Ne IV, Ne V, Ne VIII, Na I, Na IX, Na X, Mg I, Mg II, Mg XI, Al I, Al III, Al V, Al XI, Si I, Si IV, Si V, Si VI, Si XI, Si XII, Si XIII, P IV, P V, P VI, S III, S IV, S V, S VI, Cl I, Cl IV, Cl VI, Cl VII, Ar I, Ar II, Ar III, Ar IV, Ar VIII, K I, K VIII, K IX, Ca I, Ca II, Ca V, Ca IX, Ca X, Sc III, Sc X, Sc XI, Ti IV, Ti XI, Ti XII, V V, V XIII, Co I, Cr II, Mn II, Mn III, Fe II, Co III, Ni II, Cu I, Zn I, Ga I, Ga III, Ge I, Ge III, Ge IV, Se I, Br I, Kr I, Kr II, Kr VIII, Rb I, Sr I, Y III, Pd I, Ag I, Cd I, Cd II, Cd III, In II, In III, Te I, I I, Ba I, Ba II, Au I, Hg II, Tl III, Pb IV, and Ra II. In total, Stark broadening parameters have been calculated and published for 123 atomic and ionic species for 49 chemical elements, during a period of more than thirty years.

The obtained Stark broadening data have been used and cited many times for various applications and investigations. The literature where Stark broadening data might be used (as described in more detail previously) has been analyzed many times, but the set of data considered here allows examination of the purposes such data have actually been used for. This is interesting to analyze not only in order to demonstrate the possibilities of their applicability but first of all to see the needs of their principal users in order to adapt the presentation of results and plans for future investigations in accordance with the needs of consumers of such results. We will exclude from this analysis applications and citations concerning the theoretical and experimental research of Stark broadening and consider only applications in other research fields, published in international journals.

2. Applications of Stark Broadening Data Obtained by the Semiclassical Perturbation Method for Astrophysical Research

The analysis of citations of Stark broadening data obtained by semiclassical perturbation method shows that the largest number of citations is for astrophysical applications. For various investigations in astrophysics, our data for He I, Na I, C IV, Si II, Si IV, Li I, N V, Hg II, O VI, S VI, Mg I, Mg II, Ba I, Ba II, Ca I and Ca II have been used.

After hydrogen, helium has the largest cosmic abundance, so it is not surprising that our Stark broadening data for He spectral lines [3–7] have often been used for different investigations in astrophysics [8–83]. For example, they have been used for the following astrophysical problems: non Local Thermodynamical Equilibrium (LTE) model analysis of the interacting binary Beta Lyrrae [8], research of variability of Balmer lines in Ap stars [9], consideration if Delta Orionis C and HD 58260 of peculiar helium-strong stars [10], determination of the chemical composition of two double clusters and of a loose association [11], the critical analysis of the ultraviolet temperature scale of the helium-dominated DB and DBV white dwarfs [12], the effective temperature calibration of MK spectral classes dwarf stars using spectral synthesis [13], investigation of the extreme helium star BD-90-4395 [14], the ionization and excitation of hydrogen and helium in cool giant stars [15], the constitution of the atmospheric layers and the extreme ultraviolet-spectrum of hot hydrogen-rich white dwarfs [16], interpretation of spectral properties of hot hydrogen-rich white dwarfs with stratified H/He model [17], radiative accelerations on iron [18], non-LTE radiative acceleration of helium in the atmospheres of sdOB stars [19], research of hot stars with peculiar helium and noble gas abundances [20,25], a spectroscopic analysis of DAO and hot DA white dwarfs with the investigation of the implications of the presence of helium in the stellar nature [21]. The considered Stark broadening data have been entered into a spectrum synthesis program for binary stars [22] and have been used for the helium surface mapping and spectrum variability considerations of ET Andromedae [23,26], for the investigation of the He λ10830 Å spectral line formation mechanism in classical cepheides [24], for the consideration of hot white dwarfs in the Extreme-Ultraviolet Explorer survey [27], for the search for forced oscillations in eclipsing and spectroscopic binaries [28], for investigations of the evolutionary state and helium abundance in He-rich stars [29] and the consideration of how much hydrogen is in white dwarfs [49], for a study of the effect of diffusion and mass-loss on the helium abundance in hot white dwarfs and subdwarfs [30], for the spectral analysis of the low gravity extreme helium stars [51] and a field horizontal-branch B-type star [83], for comparison with theoretical results obtained within the Stark broadening theory of solar Rydberg lines in the far infrared spectrum [58], for the research of dynamic processes in Be star atmospheres based on the example of He I 2P-nD line formation [59], for the investigation of winds of hot stars [60], for a study of the atmospheric variations of a peculiar Be star [61], for the application of a new tool for fitting observations with synthetic spectra [62], for the determination of the abundance of 3He isotope in HgMn star atmospheres [63], and for the investigation of the helium stratification in the atmospheres of magnetic helium peculiar B-type stars [64].

Results for Si II ion lines [84], obtained within the semiclassical perturbation method have been applied in numerous astronomical researches of stellar atmospheres, such as e.g. in [85–131]. The data have been used for silicon abundance analyses for a number of A (mainly) and B type stars [85–88,91–93,97,99,101,103,105,106,109–111,113–118] but also for normal F main sequence stars [89,112]. The discussed Si II Stark broadening data have also been used for an investigation of blue stragglers of M 67 [90], 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 [94], analysis of the red spectrum of Ap stars [95], non-LTE analysis of subluminous O type hot subdwarf in the binary system HD 128220 [98], a discussion on the significance of Stark spectral line shifts for element abundance determination with the method of atmospheric model [102], a discussion of the nature of the F STR λ 4077 type stars [104] and have been used for atmosphere research, He surface mapping and spectrum variability considerations of ET Andromedae [107,108].

Results obtained for lithium [132] have been used for a study of the non-LTE formation of Li I lines in cool stars [133] and Stark-broadening parameters of ionized mercury spectral lines [134], have been used for determination of Hg abundances in normal late-B and HgMn stars from co-added spectra from International Ultraviolet Explorer [135].

Our data for Ca II [136,137] have been used for the calcium abundance analysis of the double-lined spectroscopic binary α Andromedae [138], for the investigation of the pressure shifts and abundance gradients in the atmosphere of a DAZ white dwarf [139], for the analysis of VLT/X-shooter observations in order to determine the chemical composition of cool white dwarfs [140], and for abundance analysis of two late A-type stars [141].

Mg I [142,143] Stark broadening parameters have been used for analysis of stellar atmospheric parameters [144], for a non-LTE analysis of Mg I in the solar atmosphere [145], investigation of A-type stars [146,147] and for astrophysical tests of atomic data for the stellar Mg abundance determination [148]. Also, Mg II [149] data have been used for investigation of the pressure shifts and abundance gradients in the atmosphere of a DAZ white dwarf [139].

Na I [150] data were used for non-LTE calculations for neutral Na in late-type stars [151] and, Ba I and Ba II data [152,153] for abundance analysis of late A-type stars [154] and for quantitative spectroscopy of Deneb [155].

Results for multiply charged ions C IV [156], Si IV [157], N V [158], O VI [159] and S VI [160] have been used for non-LTE analysis of a SDO binary [161], analysis of PG 1159 stars [162] with the accent on the influence of gravitational settling and selective radiative forces [163], for high resolution UV spectroscopy of hot (pre-)white dwarfs with the Hubble Space Telescope [164], spectral energy distribution and the atmospheric properties of a helium-rich white-dwarf [165], for an investigation of stellar masses, kinematics, and white dwarf composition for three close DA+dMe binaries [166], for the calculation of C IV, N V, O VI and Si IV resonance lines formed in accretion shocks in T Tauri stars [167], for analysis of UV spectroscopic data for central star of Sh 2-216, obtained by the Far Ultraviolet Spectroscopic Explorer (FUSE) and the Hubble Space Telescope [168], for the spectral analysis of planetary nebulas K 1-27 [169,170] and for their very hot hydrogen-deficient central stars. These data have also been used for the study of the extreme ultraviolet (EUV) spectrum of the unique bare stellar core H1504+65 [171], for analysis of the FUSE spectra of a He-poor SDO star [172] and of a hot evolved star [173], GD 605, as well as for the analysis of He I lines in atmospheres of B-type stars [174] and for iron opacity predictions under solar interior conditions [175].

3. Applications of Stark Broadening Data Obtained by the Semiclassical Perturbation Method for Research in Physics and for Plasmas in Technology

If we do not take into account the usage of Stark broadening data for theoretical and experimental research of Stark broadening, the applications of Stark broadening parameters obtained by semiclassical perturbation method are not as numerous as in astrophysics. Semiclassical Stark broadening parameters of He I, Li II, Be II, Na I, Ca I, Ca II, Mg I, Mg II, Sr I, Ba I, Ba II, Zn I, Ag I, Cd I, Cu I, Ar I, Ar VIII, Al III, C IV and S V have been used for various physical problems.

Stark broadening data for helium [3,5] have been used for the analysis of the measurements of the hyperfine structure of the 1s3s3S1 state of Helium 3 [35], for the determination of emission coefficients of low temperature thermal iron-helium plasma [44] and for the analysis of the net emission of Ar–H2–He thermal plasmas at atmospheric pressure [57].

Na I data [174] have been used for the derivation of electron density radial profiles from Stark broadening in a sodium plasma produced by laser resonance saturation [175] and for the study of the mechanisms of resonant laser ionization [176], Be II [177] data for oscillator strength ratio measurements [178], Ca I [179,180] for the determination of differential and integrated cross sections for the electron excitation of the 41Po state of calcium atom [181] and for investigation of charged particle motion in an explosively generated ionizing shock [182], Ca II [137] for chlorine detection in cement with laser-induced breakdown spectroscopy [183] and for dynamical plasma study during CaCu3Ti4O12 and Ba0.6Sr0.4TiO3 pulsed laser deposition [184], Mg I [185] and Mg II [186] for consideration of plasma plume induced during laser welding of magnesium alloys [187], Sr I [188] for investigation of vapor-phase oxidation during pulsed laser deposition of SrBi2Ta2O9. [189], for the measurement and control of ionization of the depositing flux during thin film growth [190] and for space and time resolved emission spectroscopy of Sr2FeMoO6 laser induced plasma [191], Li II [192] for examination of spatial and temporal variations of electron temperatures and densities from EUV-emitting lithium plasmas [193] and for modeling of continuous absorption of electromagnetic radiation in dense partially ionized plasmas [194], Ba I and Ba II [152,153] for investigation of plasma properties of laser-ablated strontium target [195] and for laser-based optical emission studies of barium plasma [196], Ag I [197] for determination of absolute differential cross sections for electron excitation of silver at small scattering angles [198], Cd I [199] for investigation of cadmium plasma produced by laser ablation, namely for its diagnostics [200], for comparison with zinc plasma [201] and for the research and diagnostics of deposition of wide bandgap semiconductors and nanostructure of deposits [202], Cu I [203] for investigation of characteristics of plume plasma and its effects on ablation depth during ultrashort laser ablation of copper in air [204] and Ar I [205] for spectroscopic investigation of the high-current phase of a pulsed gas metal arc welding (GMAW) process [206], for consideration of characteristics of plasma spray-physical Vapor Deposition (PVD) and impact on coating properties [207], for measurement of the temporal evolution of electron density in a nanosecond pulsed argon microplasma [208] and for the study of metal transfer in CO2 laser+GMAW-P hybrid welding using argon-helium mixtures [209].

Stark broadening parameters of Zn I spectral lines [210] have been used for experimental verification of a radiative model of laser-induced plasma expanding into vacuum [211], analysis of optical emission for the optimization of femtosecond laser processing [212], diagnostics of a laser-induced zinc plasma [213], comparison of zinc and cadmium plasma produced by laser ablation [201], spectroscopic characterization of laser ablation brass plasma [214], stoichiometric investigations of laser-ablated brass plasma [215], investigation of laser ablation and deposition of wide bandgap semiconductors and nanostructure of deposits [202], research of photoluminescence of nanoparticles in vapor phase of colliding plasma [216], consideration of the role of laser pre-pulse wavelength and inter-pulse delay on signal enhancement in collinear double-pulse laser-induced breakdown spectroscopy [217], for comparison of optical emission from nanosecond and femtosecond laser produced plasma in atmosphere and vacuum conditions [218], for investigation of dynamics of laser ablated colliding plumes [219], the investigation of brass plasmoid in external magnetic field [220], and research of emission dynamics of an expanding ultrafast-laser produced Zn plasma [221].

Stark broadening data for Al III [222] spectral lines have been used for examination of a novel plasma source for dense plasma effects [223] and for simulations of spectra from dense aluminum plasmas [224]. Data for C IV [156] have been used for the investigation of long-living plasmoids from an atmospheric discharge [225], data for S V [226] for time-integrated, spatially resolved plasma characterization of steel samples in the vacuum ultraviolet (VUV) [227], and data for Ar VIII [228] for investigation of optical emission spectra of ZnMnO plasma produced by a pulsed laser [229].

4. Conclusions

From the analysis of applications of Stark broadening parameters calculated using semiclassical perturbation method [1,2] one can conclude that principal users of such data are astronomers, using them especially for the investigation of A and B type stars, white dwarfs and hot stars in evolved evolution stages (especially PG1159 type). We note here that in white dwarf and hot pre-white dwarf atmospheres, Stark broadening is the dominant broadening mechanism in comparison with thermal Doppler broadening and for atmospherae modeling, spectra analysis and synthesis, abundance determination, radiative transfer calculation or plasma diagnostics, the knowledge of reliable Stark broadening parameters is essential. For A type stars, Stark broadening is the principal pressure broadening mechanism and often an important correction, the neglect of which may introduce serious errors, especially in abundance determinations. For B-type stars, especially for later types, Stark broadening may also be a non-negligible correction. The most used data are for spectral lines of He I and Si II. Concerning plasmas in physics and technology, the most frequent applications concern laser produced plasma, and the most used data are Stark broadening parameters of Zn I.

In order to make the application and usage of Stark broadening data obtained using the semiclassical perturbation method easier, the here analyzed data are displayed online in the STARK-B database [230], which is part of the Virtual Atomic and Molecular Data Centre—VAMDC [231].

Acknowledgments

This paper is part of the projects 176002 and III44022 of the Ministry of Education, Science and Technological Development of Republic of Serbia. This work was also done within the LABEX Plas@par project and received financial state aid managed by the Agence Nationale de la Recherche, as part of the program "Investissements d'avenir" under the reference ANR-11-IDEX-0004-02.

Conflict of Interest

The authors declare no conflict of interest.

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