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STARK-B DATABASE FOR STARK BROADENING FOR ASTROPHYSICAL PLASMA ANALYSIS AND MODELLING

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Abstract. The creation and development of STARK-B database (http://stark-b.obspm.fr) is a collaborative project between the "Laboratoire d'Étude du Rayonnement et de la matière en Astrophysique" (LERMA) of the Paris Observatory and CNRS, and the Astronomical Observatory of Belgrade (AOB). Database contains widths and shifts of isolated lines of atoms and ions due to electron and ion impacts (Stark broadening parameters) determined theoretically in more than 150 papers by Dimitrijević, Sahal-Bréchot, and colleagues, and published in international journals. Here we present the state of advancement as well as our programme of its further development. Applications of Stark broadening parameters from STARK-B are also discussed. This database enters in Virtual Atomic and Molecular Data Center (VAMDC – http://www.vamdc.eu).

1. INTRODUCTION

Stark broadening of spectral lines arises when an atom or an ion which emits or absorbs radiation in a gas or in a plasma, is perturbed by interactions with charged particles of the medium. Theoretical and experimental investigations in this research field were stimulated by needs for such data in Astrophysics, for laboratory plasma diagnostics, different applications in Physics (e.g. laser produced plasmas, inertial fusion plasmas…), and also by the needs in industrial plasmas (discharge lighting, laser welding and piercing of metals...). Due to the developments of space born spectroscopy the accuracy of observations in astrophysics is constantly increasing, as well as the number of atomic data

including Stark broadening parameters, needed for the interpretation and analysis of obtained spectra. The development of new generations of powerful computers also enabled sophysticated investigations needing a large number of atomic data as well as their production on a large scale. Consequently, the possibility to access such atomic data via on line databases becomes essential.

Already about thirty years, two of us (MSD-SSB) have operated at a large scale the computer code created by Sahal-Bréchot (1969a, 1969b) and later update and optimized several times (see the review of updates in Sahal-Bréchot et al. 2014), for example: Sahal-Bréchot (1974) for complex atoms, Fleurier et al. (1977) for the inclusion of Feshbach resonances in the elastic ion-electron cross-sections, Dimitrijević and Sahal-Bréchot (1984) and further papers, and Mahmoudi et al. (2008) for transitions arising from very complex configurations. The code is based on the impact semiclassical-perturbation theory (SCP) for isolated spectral lines of neutral and ionized atoms broadened and shifted by collisions with electrons and ions, and gives Stark broadening parameters, spectral line widths and shifts. It was used to calculate results published in more than 150 papers so that the need of creation of an on-line database appeared.

Thus, the database STARK-B (formerly called BELDATA) was initiated in the Astronomical Observatory of Belgrade (AOB), and then a collaborative project between AOB and LERMA was born and led to the present database. A history of BELDATA can be followed in Popović et al. (1999a,b), Milovanović et al. (2000a,b), Dimitrijević et al. (2003) and Dimitrijević and popović (2006).

Actualy, the STARK B database, is on-line in free access, since the end of 2008 (http://stark-b.obspm.fr Sahal-Bréchot et al. 2012). It is currently maintained and developed at Paris Observatory and now contains the Stark broadening parameters, obtained by using the SCP theory and code, from all our papers. We note that there is a link to the Serbian Virtual Observatory (SerVO, http://servo.aob.rs/~darko) at AOB, where latter, a mirror site is planned. STARK-B is also a database included in VAMDC (Virtual Atomic and Molecular Data Centre), an FP7 European project "Research Infrastructures" which has been created in summer 2009 for 3.5 years, in order to create an interoperable e-infrastructure for search and exchange of atomic and molecular data (Dubernet et al. 2011, Rixon et al. 2011 - http://www.vamdc.eu, and http://portal.vamdc.eu).

Here, the STARK-B database is presented and described as well as the plans for its future development.

2. THE STARK-B DATABASE

On the homepage of STARK-B database, proposed menus are "Introduction", "Data Description", "Access to the Data", "Updates" and "Contact". In "Introduction" are described methods used for Stark broadening parameter calculations and different approximations. "Data Description" describes the tabulated data. "Access to the Data" offers a graphical interface which enables to click on the desired element in the Mendeleev periodic table and after this on the

needed ionization degree. Stark broadening parameters are present for elements in yellow cells, with symbols enhanced by boldface, while for elements in other cells, with the lighter color, there is no data. After choosing the element and ionization stage, the visitor should choose the colliding perturber(s), the perturber density, the transition(s) and the plasma temperature(s). It is possible also to search a domain of wavelengths instead of transitions. Finally, a table containing the Stark full widths at half maximum of intensity and shifts appears. Before the Table is an instruction how to cite the STARK-B, as well as the bibliographic references for the data in the Table, which are linked to the publications via the SAO/NASA ADS Physics Abstract Service (http://www.adsabs.harvard.edu/) and/or within DOI, if available. The Stark broadening parameters, widths and shifts, can be obtained as an ASCII table or in format adapted for Virtual Observatories - VOTable format (XML format).

STARK-B displays Stark line widths W and shifts d for a set of temperatures and densities and for electrons and different ions as perturbers. The accuracy of the Stark line widths varies from about 15-20 percent to 35 percent, and in some cases up to 50 percent which depends on the degree of excitation of the upper level, on the completeness of the set of perturbing energy levels, and on the quality of the used atomic structure.

The temperature and density range covered by the tables depends on the ionization degree of the considered ion. The temperatures vary from several thousands for neutral atoms to several millions of Kelvin for highly charged ions. The electron or ion densities vary from 10^{12} (case of stellar atmospheres) to several 10^{22} cm^{-3} (some white dwarfs, subphotospheric layers and some laboratory and fusion plasmas). For the densities lower than the lowest density in the tables, the data can be obtained through a linear extrapolation. At high densities some data are not provided since the impact approximation is not more valid; an asterisk, instead of the data, indicates this. An asterisk preceding the data, denotes that the impact approximation reaches its limit of validity, i.e. when the product of density and typical collisional volume is larger than 0.1 and smaller or equal to 0.5.

With the increase of the density, when the Stark width becomes comparable to the separation between the perturbing energy levels and the initial or final level, the isolated line approximation becomes invalid. The limit of validity of this approximation is indicated in the database by a parameter C defined in Dimitrijević and Sahal-Bréchot (1984) and in following papers. For a perturber density N lower than the limiting value N_{lim} (cm^{-3}) = C/W, the line can be treated as isolated even if a weak forbidden component due to the failure of this approximation remains in the wing.

The definition of configurations, terms and levels follow the VAMDC standards, in order to allow interoperability with other atomic databases. The wavelengths (Å units) in the tables are in majority calculated from the energy levels used as input data. So, they are most often different from the measured ones

and for the identification of lines it is better to use the configurations, terms and levels.

Actually (1st of July 2014) in the STARK-B are Stark broadening parameters obtained by using the SCP method for 79 transitions of He, 61 Li, 29 Li II, 19 Be, 30 Be II, 27 Be III, 1 B II, 12 B III, 148 C II, 1 C III, 90 C IV, 25 C V, 1 N, 7 N II, 2 N III, 1 N IV, 30 N V, 4 O I, 12 O II, 5 O III, 5 O IV, 19 O V, 30 O VI, 14 O VII, 8 F I, 5 F II, 5 F III, 2 F V, 2 F VI, 10 F VII, 25 Ne I, 22 Ne II, 5 Ne III, 2 Ne IV, 26 Ne V, 20 Ne VIII, 62 Na, 8 Na IX, 57 Na X, 270 Mg, 66 Mg II, 18 Mg XI, 25 Al, 23 Al III, 7 Al XI, 3 Si, 19 Si II, 39 Si IV, 16 Si V, 15 Si VI, 4 Si XI, 9 Si XII, 61 Si XIII, 114 P IV, 51 P V, 6 S III, 1 S IV, 34 S V, 21 S VI,2 Cl, 10 Cl VII, 18 Ar, 2 Ar II, 9 Ar VIII, 32 Ar III, 51 K, 4 K VIII, 30 K IX, 189 Ca, 28 Ca II, 8 Ca V, 4 Ca IX, 48 Ca X, 10 Sc III, 4 Sc X, 10 Sc XI,10 Ti IV, 4 Ti XI, 27 Ti XII, 26 V V, 33 V XIII, 9 Cr I, 7 Cr II, 6 Mn II, 3 Fe II, 2 Ni II, 9 Cu I, 32 Zn, 18 Ga, 11 Ge, 3 Ge IV, 16 Se, 4 Br, 11 Kr, 1 Kr II, 6 Kr VIII, 24 Rb, 33 Sr, 32 Y III, 3 Pd, 48 Ag, 70 Cd, 1 Cd II, 18 In II, 20 In III, 4 Te, 4 I, 14 Ba, 64 Ba II, 6 Au, 7 Hg II, 2 Tl III and 2 Pb IV.

Under the menu "Updates" is the description of newly added data with the date of importation as well as the date of the first importation and the importation of the modification for revised data are given. Additionally, for enquiries or user support, at the end is the menu "Contact" enabling to send an e-mail with questions to the any of four authors of this article.

3. FURTHER DEVELOPMENT OF STARK-B

The stage one of the STARK-B database was the inclusion of all our SCP results. The beginning of the stage two was the development and implementation of the formulae enabling to fit the tabulated data with temperature. In order to do this, we have derived (Sahal-Bréchot et al., 2011) a simple and accurate fitting formula based on a least-square method:

$$\log (W) = a_0 + a_1 \log (T) + a_2 \log (T)^2,$$
$$d/W = b_0 + b_1 \log (T) + b_2 \log (T)^2.$$

Consequently, in STARK-B, under each table with Stark broadening parameters, a table with coefficients a_0 , a_1, a_2 and b_0 , b_1, b_2, enabling fitting with the temperature using above equations, is added.

We will develop and implement also, the fitting formulae as functions of perturber densities in order to make easier the use of data on high densities.

Within the STARK-B second stage, we also begin to implement Stark broadening data obtained with the Modified semiempirical method (MSE) (Dimitrijević and Konjević 1980; Dimitrijević and Kršljanin 1986, Dimitrijević and Popović 2001). We use this method when the needed atomic data set is not sufficiently complete to perform an adequate semiclassical perturbation

calculation. Stark line widths and in some cases also shifts of spectral lines of the following emitters have been calculated up to now:

Ag II, Al III, Al V, Ar II, Ar III, Ar IV, As II, As III, Au II, B III, B IV, Ba II, Be III, Bi II, Bi III, Br II, C III, C IV, C V, Ca II, Cd II, Cl III, Cl IV, Cl VI, Co II, Cu III, Cu IV, Eu II, Eu III, F III, F V, F VI, Fe II, Ga II, Ga III, Ge III, Ge IV, I II, Kr II, Kr III, La II, La III, Mg II, Mg III, Mg IV, Mn II, N II, N III, N IV, N VI, Na III, Na VI, Nb III, Nd II, Ne III, Ne IV, Ne V, Ne VI, O II, O III, O IV, O V, P III, P IV, P VI, Pt II, Ra II, S II, S III, S IV, Sb II, Sc II, Se III, Si II, Si III, Si IV, Si V, Si VI,
Sn III, Sr II, Sr III, Ti II, Ti III, V II, V III, V IV, Xe II, Y II, Zn II, Zn III, and Zr II.

Up to 1st of July 2014, MSE data for the following emitters have been implemented:

Al V, P VI, Cl IV, Cl VI, Ar IV, Mn III, Co III, Ga III, Ge III, Ge IV, Cd III and Ra II.

Plans for other future developments are: implementation of our quantum-mechanical results in STARK-B. Also, the development of additional fittings along a spectral series, for charge of the ion collider along isoelectronic sequences, and for homologous ions in order to enable to estimate by interpolation and extrapolation the data that are missing in STARK-B database. We will also implement little applets for fitting along temperatures, along a spectral series, charge of the ion collider along isoelectronic sequences, homologous ions… in order to enable the obtaining of data that are missing in the database.

STARK-B database is devoted to modelling and spectroscopic diagnostics of stellar atmospheres and envelopes, as well as for laboratory plasmas, laser equipment and technological plasmas investigations and will be useful for a number of topics in astrophysics, physics and technology.

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