AIP | Conference Proceedings

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Citation: AIP Conf. Proc. **645**, 67 (2002); doi: 10.1063/1.1525437

View online: http://dx.doi.org/10.1063/1.1525437

View Table of Contents: http://proceedings.aip.org/dbt/dbt.jsp?KEY=APCPCS&Volume=645&Issue=1

Published by the American Institute of Physics.

Diagnostics Of Detached Plasmas Using High-*n* Lines And Continuum Spectra Of D and He

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Abstract. A Stark line shape code has been coupled to a collisional-radiative model and to an analytical model for the merging into the continuum of the Balmer lines. The coupled codes have been used for temperature and density diagnostics of detached plasmas. In contrast with the occupation probability and the lowering of the continuum edge approaches, the analytical line merging model used here consists in the use of Lorentzian profiles for highly excited Balmer transitions of deuterium. In addition, high-n helium lines (1s2p-1sn*l*) up to *n*=12 observed in the JET divertor have been preliminary analyzed. The intensities of these experimental helium lines decrease more rapidly with the upper state n*l* than the intensities calculated with state populations at local thermodynamic equilibrium (LTE).

I. INTRODUCTION

In present magnetic fusion devices, the creation of a radiating cold dense plasma in the periphery (near the limiter or in the divertor chamber) is a common way to solve the problem of the wall erosion by strong particle and heat fluxes escaping from the core plasma. This cold layer has the important property of limiting both the impurity ionization to low stages and their penetration into the confined plasma. Through their interactions with the plasma particles, the main intrinsic impurities transform an important quantity of escaping energy into an isotropic radiation. Under such conditions, highly excited levels of deuterium are populated by recombination allowing high-n lines of the Lyman, Balmer, and Paschen series to be observed. Lines of the Lyman series are optically thick while those of the Paschen series are in the ultraviolet frequency domain. Lying in the visible domain, the lines of the Balmer series are easily measured in several machines. In JET [1-2] as well as in other Tokamaks like Alcator C-Mod [3], spectra extending beyond the Inglis-Teller limit and beyond the Balmer series limit have been measured. Being dominated by Stark broadening the full widths of the isolated lines of the spectra are usually fitted to deduce the electron density of the plasma. The electron temperature is deduced for example by using line intensity ratios and assuming a LTE for the level populations. To improve both the plasma electron and temperature diagnostics we fit the whole

CP645, *Spectral Line Shapes: Volume 12, 16th ICSLS*, edited by C. A. Back

Balmer spectrum of deuterium instead of using Stark widths of individual lines. The method is based on a Stark line-shape code, on a model for the line-merging into the continuum and on a collisional-radiative model for the level populations. These self-consistent codes to be described in the following are incorporated in a fitting procedure. The experimental spectra are fitted with this procedure in order to determine the electron density, the electron and ion temperatures, the recombination state of the plasma and even the concentration of impurities under some conditions.

II. THE SPECTRAL MODELLING CODES

The Stark profiles of isolated Balmer lines are calculated using a standard version of the PPP line shape code [4]. This version uses the impact and the quasi-static approximations [5] to treat the homogeneous and inhomogeneous broadenings due respectively to the plasma electrons and ions. Though one of the main characteristics of the PPP code is its capability to treat the ion dynamics effect, this latter has been ignored in the calculations presented here. For practical reasons we have limited the use of the PPP code to the profiles of Balmer lines with wavelengths $\lambda \geq 3712$ Å, i.e., the D_{15} line wavelength (transition n=15 $\rightarrow$ n'=2). Examples of Stark profiles of some Balmer lines (lines D_{10} to D_{15}) calculated by PPP for three values of the electron density are shown in Figure 1. One can clearly see that as Stark effect increases with both the upper quantum number n and the electron density Ne, high n lines broaden and merge together.

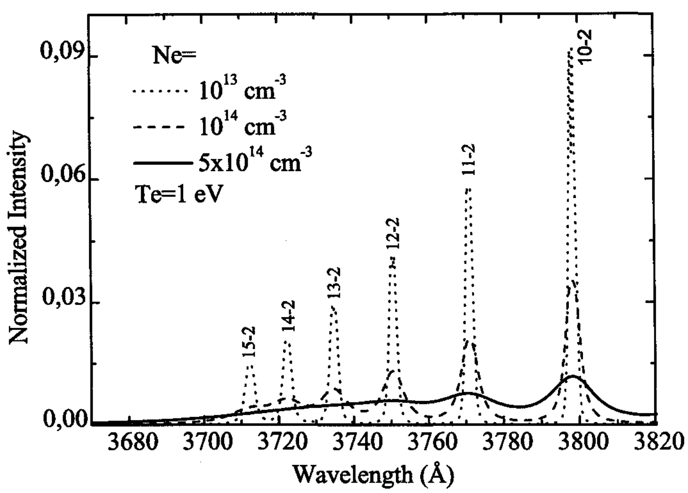

FIGURE 1. Stark profiles of some high-n deuterium Balmer lines calculated using the PPP code for an electron temperature Te=1 eV and three values of the electron density Ne: 10^{13} cm^{-3} (dot), 10^{14} cm^{-3} (dash), and 5x10^{14} cm^{-3} (solid). As Stark effect increases with the upper quantum number n and the electron density Ne, high-n lines broaden and merge together for the highest value of Ne.

It should be noted that the other part of the bound-bound emission, i.e., Balmer transitions with n greater than 15, is treated with an analytical continuity model of smooth line merging into the continuum.

II.1. An Analytical Continuity Model For The Line Merging Into The Continuum

Bound-bound emission is separated into two terms representing respectively the 'discrete' and the 'blended' lines. The former lines are calculated using the PPP code as mentioned above while the 'blended' part of the bound-bound emission spectrum is treated with a new approach. This approach of smooth merging of lines into the continuum [6-7], is completely different from the occupation probability [3,8] or the artificial lowering of the continuum edge [9] approaches. The basic idea of the line merging model used here is to introduce line profiles in the continuum part of the emission spectrum and to consider population elements when approaching the ionization threshold instead of the usual discrete quantum shells. The formalism applied for the isolated (or discrete) Balmer lines is extended to overlapping Balmer lines, i.e., transitions from highly excited levels (upper quantum number PQN n=16 to n=100) to the n'=2 lower level. The populations of these levels are calculated using the ADAS [10] collisional-radiative model. As the series limit is approached the lines broaden and merge together with the merged lines smoothly extending through the continuum. We have used Lorentzian profiles to model the emission of these highly excited levels. For simplicity all the Lorentzian widths γ have been taken equal to the width γ_{16} of the D_{16} line. This latter, γ_{16}, is consistently calculated for each couple of electron density and temperature (Ne, Te), by extrapolating the widths of the corresponding discrete lower lines. In conclusion, the bound-bound emission is treated by the PPP code and the Lorentzian profiles. Bound-bound emission has now a contribution at continuum wavelengths as it can be seen on figure 2. Inversely, as it will be shown in the next subsection, the bound-free emission treated here in a standard way has also a contribution at bound-bound wavelengths. Figure 3 shows the bound-free contribution.

II.2. Bound-Free Emission Profile

The bound-free emission profile is calculated from the corresponding emission coefficient [11] defined as the number of photons emitted at a wavelength λ per unit time, per unit volume, per unit solid angle at position L:

$$\varepsilon_{bf} = L\frac{1}{4\pi}\left[N_i f(\mathrm{v}) b_\kappa d\mathrm{v}\right]\left[N_e \mathrm{v}\sigma_{\kappa n}\right], \qquad (1)$$

where $f(\mathrm{v})$ and $\sigma_{\kappa n}$ are respectively the Maxwellian velocity distribution of free electrons and the target area for their capture, b_κ is the bound b-factor (deviation factor from a Maxwellian distribution) extended into the continuum, and Ne and Ni are the electron and ion densities.

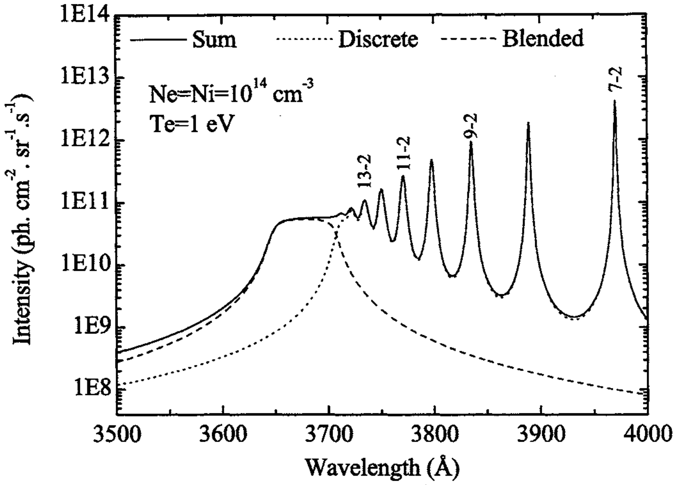

FIGURE 2. Bound-bound emission intensity. The bound-bound emission profile (solid) is the sum of the lower Balmer lines (with $n \leq 15$) labeled 'discrete' here (dot) and the 'Blended' part (dash). Note the semi-logarithmic scale and that the wavelength domain includes the D_7 (transition n=7→n'=2) line at ~3970 Å.

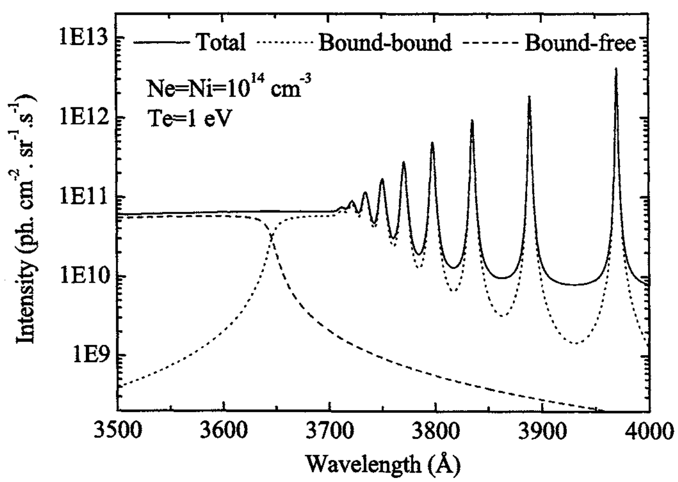

FIGURE 3. A synthetic profile of the deuterium Balmer emission for Ne=Ni=10^{14} cm^{-3} and Te=1 eV. The total profile (solid) is the sum of the bound-bound (dot) and bound-free (dash) emission profiles. The wavelength domain is the same as in figure 2, i.e., lines D_n with $n \geq 7$ are included in the profile.

III. THE FITTING ROUTINE AND ITS APPLICATION

The codes mentioned above have been coupled together and incorporated in a powerful fitting procedure capable of extracting more accurate electron density and temperature. Other information can be extracted too as the recombination state, the ion temperature and the impurity concentration. To illustrate that, we show in figure 4 an example of a fitted JET spectrum and in figure 5 the residual.

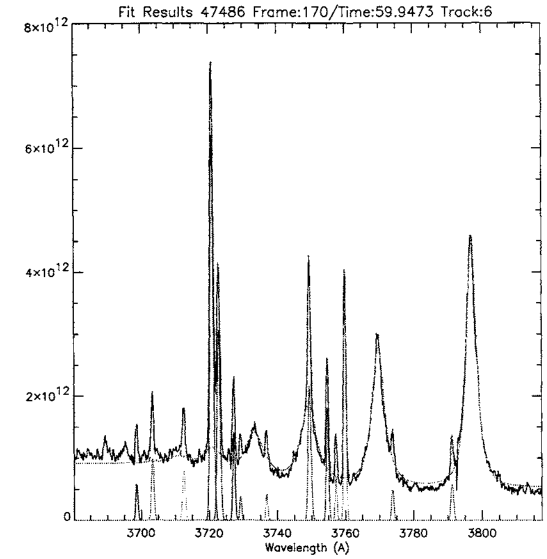

FIGURE 4. A fit of a Balmer spectrum emitted by deuterium in the axisymmetric divertor of JET. The experimental spectrum is in solid lines while the calculated one is in dotted lines. Note the presence of impurity lines fitted with gaussians. The plasma parameters inherent from the fit are Ne=Ni=$8x10^{13}$ cm^{-3} and Te=0.75 eV.

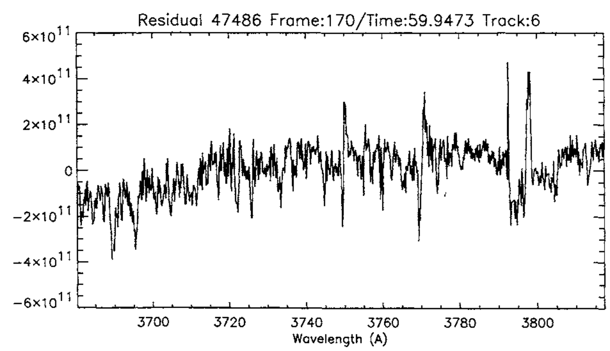

FIGURE 5. The residual of the fitting of the experimental spectrum presented in figure 4. It should be noted the likely presence of an extra impurity line at ~3797 Å.

On figure 4, one can see the good agreement between the experimental spectrum (solid) and the fitting feature (dot). The plasma parameters deduced from the fit are Te=0.75 eV and Ne=Ni=$8x10^{13}$ cm^{-3}. Impurity lines are also fitted here with Gaussians. One can also see that the last resolved member of the Balmer series is the D_{15} line, indicating an upper limit for the electron density of 10^{14} cm^{-3} which is the Inglis-Teller limit [12]. Note that the continuum is reached at ~3705 Å instead of ~3645 Å, which is the conventional value of the continuum edge of the hydrogen Balmer series.

IV. HIGH *n* LINE SPECTRA OF NEUTRAL HELIUM

In some JET helium discharges with a strong deuterium puffing spectra of high-n lines of neutral helium have been measured in the divertor region. A typical spectrum is shown in figure 6. One can identify one singlet line and five triplet lines. The triplet lines represent transitions 1s2p-1s*nl* with *n*=8,9,10,11 and 12, *l* being equal to 0 or 2 (s or d states). In figure 6 we have added to the experimental spectrum (solid) a calculated one using the PPP code with a hydrogen-like electron collision operator, and assuming a LTE for the state populations. It is clear that the experimental intensities of the lines decrease more quickly with the PQN *n* than the calculated one. This indicate that a collisional-radiative model allowing population transfer between the singlet and triplet state systems is needed. This is in progress.

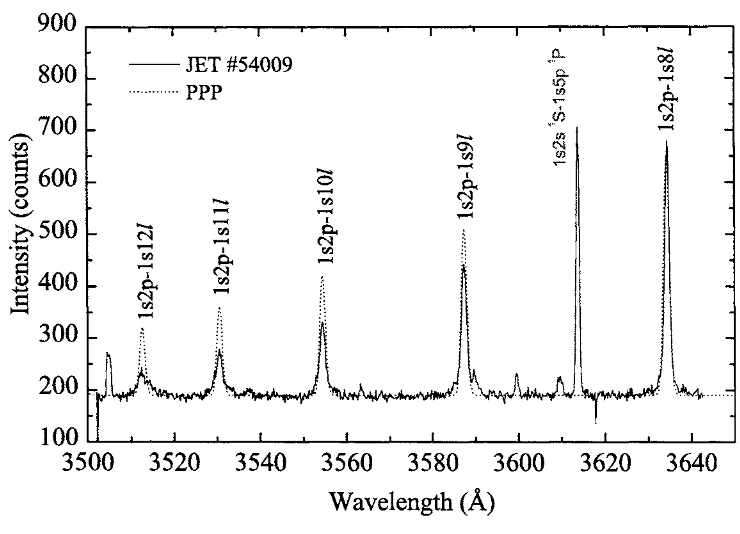

FIGURE 6. A comparison between an experimental spectrum of neutral helium (solid lines) with a synthetic profile (dashed). The latter was calculated using the PPP code with a hydrogen-like electron collision operator and assuming a LTE for the level populations. Note that experimentally the line intensities decrease more rapidly with the PQN n than theoretically.

V. CONCLUSION

We have presented a robust procedure to fit high-*n* lines and continuum spectra of deuterium in dense plasmas (detachment conditions or recombining plasma regimes). The procedure is based on the use of a Stark broadening lineshape code, a collisional-radiative model and an analytical model for the merging of high members of the Balmer series into the continuum. The latter requires the introduction of Lorentzian profiles which have contributions at bound-free wavelengths. An illustration of the capabilities of the procedure to determine plasma parameters has been presented. On the other hand, a spectrum of neutral helium including high-n triplet lines 1s2p-1s*nl* with *n* between 8 and 12 has been compared to a calculation using a standard Stark lineshape code and assuming a LTE for the state populations. The rapid decrease of the intensities of the lines with n indicate the necessity to couple singlet and triplet state systems in any collisional-radiative model to fit the experimental spectrum.

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