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Review of the 1st Spectral Line Shapes in Plasmas code comparison workshop

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A R T I C L E I N F O

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1. Introduction

Line-shape analysis is one of the most important tools for diagnostics of both laboratory and space plasmas [1]. Its reliable implementation requires sufficiently accurate calculations. In the formation of a line shape Stark broadening is the most computationally challenging contribution, with other factors, such as the Zeeman and Doppler effects, further complicating the calculations. Therefore, except for limiting cases, line-shape calculations imply the use of computer codes of varying complexity and requirements of computational resources. There exist several such codes and, necessarily, limits of applicability, accuracy, and in the end, results, differ from one to another. However, studies comparing different computational and analytical methods are almost nonexistent. The 1st Spectral Line Shapes in Plasma (SLSP) code comparison workshop [2] was organized to fill this gap. The organization of the meeting was modeled after the very successful series of NLTE workshops running from the mid 1990's [3] until now [4]. The NLTE workshops were inspired by the Opacity Workshops, initiated in the late 1980's [5], where a detailed comparison of results for a preselected set of standardized case problems was carried out and analyzed.

A general review of the SLSP workshop is presented, focusing on motivation for the case problems chosen, and followed by discussion of selected results.

ABSTRACT

A review is given of the first workshop dedicated to the detailed comparison of various approaches to the calculation of spectral line shapes in plasmas. A standardized set of case problems was specified in advance, together with the prescribed atomic data and assumptions to be used. In this brief review, motivations for the case problems chosen are outlined, followed by a discussion of selected results. Plans for the next workshop are discussed in the conclusion.

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2. Cases

A number of transitions were selected and are presented in Table 1. For each transition results on a grid of electron densities (n_e) and temperatures were requested – assuming one temperature for the ions and electrons, i.e., $T = T_e = T_i$. For each case, the atomic and plasma models are specified, and for some cases, there are more than one atomic or plasma model suggested. Here unless specified otherwise, the plasma is assumed to be quasi-neutral, consisting of electrons and a single type of ions. In addition, some cases are further detailed by specifying extra parameters, such as the magnetic field. In total, 184 subcases were defined.

In order to exclude the influence of variance of atomic data on the results, the case definitions also included exact atomic models to be used. That is, provided were a list of the levels to be accounted for, level energies, and matrix elements between them.

2.1. Reference cases

- 1. Hydrogen Lyman- α in an ideal plasma is a classical iondynamics test.
- 2. A relatively high-*n* line for hydrogen. For the plasma parameters selected, this is a test of the transition for electrons from dynamic to almost static regime.

These cases are not necessarily realistic, but are good for basic comparison and understanding what is wrong/different if there is a significant scatter in the results from the more advanced cases below. There are quite a few sub-cases of these reference cases; however, the





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| Table 1 |
|-------------------|
| Case definitions. |

| 1H Jyman- α 10 ¹⁷ , 10 ¹⁸ , 10 ¹⁹ 1, 10, 100-Model: $\Delta n \neq 0$ interactions ignored (strictly linear Stark effect); no fine structure; ideal plasma (straight path trajectories and infinite Debye length for MD or Holtsmark distribution for analytical models) in three variants: only electrons, only protons, and electrons and protons together.2H Lyman- δ 10 ¹⁶ , 10 ¹⁷ , 10 ¹⁸ 1, 10, 1003H $n = 6 \rightarrow 5$ 5×10^{15} , 2×10^{6} 1, 10-4Model: Same as above.0-5N 33-3p10 ¹⁷ 5 , 15, 50-6N VIII Sa-3p10 ¹⁸ 2, 4, 8-6N VIII Sa-3p10 ¹⁹ 5, 15, 50-7A III II 4S-4p10 ¹⁶ 2, 4, 8-Model: same as above.08S ISII In = 3 $\rightarrow 1$ 10 ²¹ , 10 ²² , 10 ²³ 300-9A XIII Lyman- α 10 ²¹ , 10 ²² , 10 ²² 500-Model: same as above.10 ²¹ , 10 ²² , 10 ²³ 300-9A XIII Lyman- α 10 ²¹ , 10 ²² , 10 ²³ 300-10Nodel: same as above.010 ¹⁵ rad/s, $F = 0, 1, 2$ GV/cmModel: M = 1 and 3 single levels included, no fine structure. Plasma ions are protons. $\theta = 10^{15}$ rad/s, $F = 0, 1, 2$ GV/cmModel: M = 1 and 3 single levels included, no fine structure. Plasma ions are protons. $\theta = 10^{15}$ rad/s, $F = 0, 1, 2$ GV/cmModel: Same as above.10 ²¹ , 10 ²² , 10 ²¹ 1-10D Baimer- α 2 × 10 ¹⁴ , 10 ¹⁵ 1 <th>ID</th> <th>Transition(s)</th> <th><i>n</i>_e (cm⁻³)</th> <th><i>T</i> (eV)</th> <th>Extra parameters</th> | ID | Transition(s) | <i>n</i> _e (cm ⁻³) | <i>T</i> (eV) | Extra parameters | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
|---|-------------------------|---|--|---------------------------------------|---|--|--|--|--|--|--|--|--|---|----|--------------------|------------------|---|---|---|--|---|--|--|--|--|--|---|----|-------------------|------------------|---|---|---|--|-----------------------|--|--|--|--|-----|--------------|---|------|---|--|--|--|--|--|--|--|--|--|-----|------------------------------|---|------|---|---|-----|------------------------------|---|------|---|---|-----|----------------------------|---|------|---|--|--|
| Model: $\Delta n \neq 0$ interactions ignored (strictly linear Stark effect); no fine structure; ideal plasma (straight path trajectories and infinite Debye length for MD or Holtsmark distribution for analytical models) in three variants: only electrons, and y protons, and electrons and protons together.2H yman-6 10^{15} , 10^{17} , 10^{16} 1, 10, 100-Model: same as above8H a = 6 - 5 5×10^{15} , 2×10^{6} 1, 10-Model: $\Delta n \neq 0$ interactions included in three approximations: none, only $n = 5$ and 6 levels included, and $H rem n = 5$ to $n = 7$. Plasma ions: protons.6Ne 13 $a - 3p$ 10^{17} 5 , 15, 50-Model: same as above7All III 45 $-4p$ 10^{18} 5 , 15, 50-Model: same as above8Nodel: same as above7All III 45 $-4p$ 10^{19} 5 , 15, 50-8Nodel: same as above8Nodel: same as above7All III 45 $-4p$ 10^{19} 2 , 4, 8-Model: $\Delta = a$ and a singlet levels only, ignoring $\Delta n \neq 0$ interactions. Plasma ions are protons8Si XIII $n = 3 \rightarrow 1$ 10^{21} , 10^{22} , 10^{23} 300 -10D Balmer ~ 2 2×10^{14} , 10^{15} 1, 5B = 0, 5, 10 TModel: $n = 1$ and 2 levels in two variants: with and without fine structure. Plasma ions are Al XIII, no electrons10D Balmer ~ 2 10^{16} , 10^{15} 1, 5B = 0, 5, 10 TModel: same as ab | 1 | H Lyman-α | 10 ¹⁷ , 10 ¹⁸ , 10 ¹⁹ | 1. 10. 100 | _ | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| for MD or Holtsmark distribution for analytical models) in three variants: only electrons, only protons, and electrons and protons together.2H lyman- δ 10 ¹⁵ , 10 ¹⁷ , 10 ¹⁸ 1, 10, 100-Model: same as above3H $\pi = 6 \rightarrow 5$ 5 × 10 ¹⁵ , 2 × 10 ⁶ 1, 10-Model: $\delta_n \neq 0$ interactions included in three approximations: none, only $n = 5$ and 6 levels interact, and all from $n = 5$ to $n = 7$. Plasma ions: protons.4Be II $3s - 3p$ 10 ¹⁷ 5Nt $3s - 3p$ 10 ¹⁸ 5N $3s - 3p$ 10 ¹⁸ 6N e Vill $3s - 3p$ 10 ¹⁹ 6N till $3s - 3p$ 10 ¹⁹ 7All III $4s - 4p$ 10 ¹⁸ 2, 4, 8-Model: $4s, 4p$, and $4d$ levels included, no fine structure. Plasma perturbations in two approximations: only electrons and both electrons and ions (AI III).8Si XII $n = 3 \rightarrow 1$ 10 ²¹ , 10 ²² , 10 ²³ 9All III $4s - 4p$ 10 ¹⁸ 2, 4, 8-Model: $4s, 4p,$ and 4d levels included, no fine structure. Plasma perturbations in two approximations: only electrons and both electrons and ions (AI III).8Si XII $n = 3 \rightarrow 1$ 10 ²¹ , 10 ²² , 10 ²³ 9Al XIII lyman- a 10 ²¹ , 10 ²² , 10 ²³ 10D $b = 0, 5, 10$ TModel: and a single levels only, ignoring $an \neq 0$ interactions. Plasma ions are protons.10D Balmer- a $2 \times 10^{14}, 10^{15}$ 11D Balmer- a $2 \times 10^{14}, 10^{15}$ 12D $n = ^{-} 2$ $10^{15}, 10^{16}, 10^{17}$ <tr<< td=""><td></td><td colspan="6">Model: $\Delta n \neq 0$ interactions ignored (strictly linear Stark effect): no fine structure: ideal plasma (straight path trajectories and infinite Debye length</td></tr<<> | | Model: $\Delta n \neq 0$ interactions ignored (strictly linear Stark effect): no fine structure: ideal plasma (straight path trajectories and infinite Debye length | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 2H Igman-ð10 ¹⁶ , 10 ¹⁷ , 10 ¹⁸ 1, 10, 100-Model: same as aboveH $n = 6 \to 5$ $5 \times 10^{15}, 2 \times 10^6$ 1, 10-Model: $\Delta n \neq 0$ interactions included in three approximations: none, only $n = 5$ and 6 levels interact, and all from $n = 5$ to $n = 7$. Plasma ions: protons.4Be II $3s \neg 2p$ 10 ¹⁷ 5N V 3s - 3p10 ¹⁸ 5S, 15, 50-Model: same as above6Ne VIII $3s - 3p$ 10 ¹⁹ 5S, 15, 50-Model: same as above7Al III $4s - 4p$ 10 ¹⁸ 2A, 8-Model: same as above8Si XII $n = 3 \rightarrow 1$ 10 ¹⁷ , 10 ²² , 10 ²³ 300Model: $n = 1$ and 3 singlet levels included, no fine structure. Plasma perturbations in two approximations: only electrons and both electrons and ions (AI III).8Si XII $n = 3 \rightarrow 1$ 10 ¹²¹ , 10 ²² , 10 ²³ 300-Model: $n = 1$ and 2 levels in two variants: with and without fine structure. Plasma ions are protons.9Al XIII Lyman- α $2 \times 10^{14}, 10^{15}$ 10Balmer- α $2 \times 10^{14}, 10^{15}$ 11D Balmer- α $2 \times 10^{14}, 10^{15}$ 12D $n = ^{4} \rightarrow 2$ $10^{15}, 10^{16}, 10^{17}$ 13H $a = 0$ $10^{15}, 10^{15}, 10^{16}, 10^{17}$ 14Balmer- β $10^{16}, 10^{17}$ 15Ar XVI He- β $10^{18}, 10^{24}, 2 \times 10^{24}$ 10D $n = ^{4} \rightarrow 2$ $10^{15}, 10^{16}, 10^{17}$ | | for MD or Holtsmark distribution for analytical models) in three variants: only electrons, only protons, and electrons and protons together | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Model: same as above.1, 10-3H n = 6 → 55 × 10 ¹⁵ , 2 × 10 ⁶ 1, 10-Model: Sam ≠ 0 interactions included in three approximations: none, only n = 5 and 6 levels interact, and all from n = 5 to n = 7. Plasma ions: protons.4Be II 3s -3p10 ¹⁷ 5, 15, 50-Model: Sam a 3 devels included, no fine structure. Only electron broadening included, in two approximations: straight paths and hyperbolic trajectories.5N V 3s -3p10 ¹⁸ 5, 15, 50-Model: same as above7A III 4s -4p10 ¹⁹ 5, 15, 50-8N 4UII 3s -3p10 ¹⁹ 5, 15, 50-9A III 4s -4p10 ¹⁸ 2, 4, 8-Model: 4s, 4p, and 4d levels included, no fine structure. Plasma perturbations in two approximations: only electrons and both electrons and ions (AI III).8Si XIII n = 3 → 110 ²¹ , 10 ²² , 10 ²³ 300-9Al XIII tyman-α10 ²¹ , 10 ²² , 10 ²³ 500ω = 10 ¹⁵ rad/s, F = 0, 1, 2 GV/cmModel: 4a, 4p, and 4d levels in two variants: with and without fine structure. Plasma ions are PIXB = 0, 5, 10 TModel: n = 1 and 2 levels in two variants: with and without fine structure. Plasma ion are Al XIII, no electrons.B = 0, 5, 10 TModel: same a above.11, 5B = 0, 5, 10 T10D almer-a2 × 10 ¹⁴ , 10 ¹⁵ 1, 5B = 0, 5, 10 TModel: same as above.112D n = * → 210 ¹⁵ , 10 ¹⁶ , 10 ¹⁷ 1-13H Balmer-a< | 2 | H Lyman-δ | $10^{16}, 10^{17}, 10^{18}$ | 1, 10, 100 | - | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 3H n = 6 → 55 × 10 ¹⁵ , 2 × 10 ⁶ 1, 10-Model: Δn ≠ 0 interactions included in three approximations: none, only n = 5 and 6 levels interact, and all from n = 5 to n = 7. Plasma ions: protons.8Be II 3s-3p10 ¹⁷ 5, 15, 50-Model: 3s, 3p, and 3d levels included, no fine structure. Only electron broadening included, in two approximations: straight paths and hyperbolic trajectories.7N V 3n-3p10 ¹⁸ 5, 15, 50-Model: same as above7A III 4s-4p10 ¹⁹ 5, 15, 50-Model: same as above7A III 4s-4p10 ¹⁹ 5, 15, 50-8Si XII n = 3 → 110 ²¹ , 10 ²² , 10 ²³ 300-Model: n = 1 and 3 singlet levels only, ignoring Δn ≠ 0 interactions. Plasma perturbations in two approximations: only electrons and ions (AI III).8Si XII n = 3 → 110 ²¹ , 10 ²² , 10 ²³ 300-8A XIII Lyman-α10 ²¹ , 10 ²² , 10 ²³ 500ω = 10 ¹⁵ rad/s, F = 0, 1, 2 GV/cmModel: n = 1 and 3 singlet levels only, ignoring Δn ≠ 0 interactions. Plasma ions are partons.9009A XIII Lyman-α10 ²¹ , 10 ¹⁶ 1, 5B = 0, 5, 10 TModel: sane as above10D Balmer-α2 × 10 ¹⁴ , 10 ¹⁵ 1, 5B = 0, 5, 10 TModel: inth/without fine structure of the lower/higher density, respectively; ideal plasma in two variants: ions are either deuterons or infinitelymassive particles.10 ¹⁵ , 10 ¹⁶ , 10 ¹⁷ 1- <td></td> <td>Model: same as above.</td> <td></td> <td></td> <td></td> | | Model: same as above. | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Model: $\Delta n \neq 0$ interactions included in three approximations: none, only $n = 5$ and 6 levels interact, and all from $n = 5$ to $n = 7$. Plasma ions: protons.4Be II 3s-3p10 ¹⁷ 5, 15, 50-Model: 3s, 3p, and 3d levels included, no fine structure. Only electron broadening included, in two approximations: straight paths and hyperbolic trajectories.5N V 3s-3p10 ¹⁸ 5, 15, 50-Model: same as above7Al III 4s-3p10 ¹⁹ 5, 15, 50-7Al III 4s-4p10 ¹⁸ 2, 4, 8-Model: same as above8Si XIII $n = 3 \rightarrow 1$ 10 ²¹ , 10 ²² , 10 ²³ 300-Model: a = 1 and 3 singlet levels only, ignoring $n \neq 0$ interactions. Plasma ions are protons.910 ¹⁵ rad/s, $F = 0, 1, 2$ GV/cm9Al XIII Lyman-α10 ²¹ , 10 ²² , 10 ²³ 300ω = 10 ¹⁵ rad/s, $F = 0, 1, 2$ GV/cmModel: n = 1 and 2 levels in two variants: with and without fine structure. Plasma ions are Ptotons.909D Balmer-α2 × 10 ¹⁴ , 10 ¹⁵ 1, 5 $B = 0, 5, 10$ TModel: same as above10D Balmer-β2 × 10 ¹⁴ , 10 ¹⁵ 1, 511D Balmer-α10 ¹⁵ , 10 ¹⁶ , 10 ¹⁷ 1-12D $n = * 2$ 10 ¹⁵ , 10 ¹⁶ , 10 ¹⁷ 1-13H Balmer-α10 ¹⁸ 1-14H Balmer-β10 ¹⁸ 1-15Ar XVII He-β5 × 10 ²³ , 10 ²⁴ , 2 × 10 ²⁴ 1000-16H Balmer-β | 3 | $H n = 6 \rightarrow 5$ | $5	imes 10^{15}, 2	imes 10^{6}$ | 1, 10 | _ | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 4Be II 3s-3p10171-Model: 3s, 3p, and 3d levels included, no fine structure. Only electron broadening included, in two approximations: straight paths and hyperbolic trajectories.N V 3s-3p1018Model: same as above6Ne VIII 3s-3p10195, 15, 50-Model: same as above7Al III 4s-4p10186x, 4p, and 4d levels included, no fine structure. Plasma perturbations in two approximations: only electrons and both electrons and ions (Al III).8Si XIII n = 3 → 110 ²¹ , 10 ²² , 10 ²³ 9Al XII Lyman-α10 ²¹ , 10 ²² 9500ω = 10 ¹⁵ rad/s, F = 0, 1, 2 CV/cmModel: n = 1 and 2 singlet levels only, ignoring Δn ≠ 0 interactions. Plasma ions are protons.9Al XIII Lyman-α10 ²¹ , 10 ²² 9500ω = 10 ¹⁵ rad/s, F = 0, 1, 2 CV/cmModel: n = 1 and 2 levels in two variants: with and without fine structure. Plasma ions are protons.10D Balmer-α10 ²¹ , 10 ¹² 101, 5B = 0, 5, 10 TModel: same as above.10 ¹⁶ , 10 ¹⁷ 11D n = * → 210 ¹⁵ , 10 ¹⁶ , 10 ¹⁷ 12D n = * → 210 ¹⁵ , 10 ¹⁶ , 10 ¹⁷ 13H Balmer-β10 ¹⁸ 14H Balmer-β10 ¹⁸ 1610 ¹⁸ 117-18Ar XVI He-β' n = 319N 2x ^{10²⁴} , 10 ²⁴ , 2 × 10 ²⁴ 1000-1010 ¹⁸ Ar XVI He-β' n = 310100015< | | Model: $\Delta n \neq 0$ interactions included in three approximations: none, only $n = 5$ and 6 levels interact, and all from $n = 5$ to $n = 7$. Plasma ions: protons, | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Model: 3s, 3p, and 3d levels included, no fine structure. Only electron broadening included, in two approximations: straight paths and hyperbolic trajectories.5N V 3s -3p10185, 15, 50-Model: same as above6Ne VIII 3s -3p10195, 15, 50-7A III 4s -4p10182, 4, 8-Model: 4s, 4p, and 4d levels included, no fine structure. Plasma perturbations in two approximations: only electrons and both electrons and ions (AI III).8Si XIII $n = 3 \rightarrow 1$ 10 ²¹ , 10 ²² , 10 ²³ 300-Model: n = 1 and 3 singlet levels only, ignoring $\Delta n \neq 0$ interactions. Plasma ions are protons9Al XIII Lyman- α 10 ²¹ , 10 ²² 500 $\omega = 10^{15}$ rad/s, $F = 0, 1, 2$ GV/cmModel: n = 1 and 2 levels in two variants: with and without fine structure. Plasma ions are AI XIII, no electrons10D Balmer- α 2 × 10 ¹⁴ , 10 ¹⁵ 1, 5 $B = 0, 5, 10$ TModel: with/without fine structure for the lower/higher density, respectively; ideal plasma in two variants: ions are either deuterons or infinitely massive particles.11D Balmer- α 10 ¹⁵ , 10 ¹⁵ , 10 ¹⁷ 112 $D n = \rightarrow 2$ 10 ¹⁶ , 10 ¹⁶ , 10 ¹⁷ 113H Balmer- α 10 ¹⁸ 114H Balmer- α 10 ¹⁸ 115Ar XVI He- β 5 × 10 ²³ , 10 ²⁴ , 2 × 10 ²⁴ 100016Ar XVI He- β 5 × 10 ²³ , 10 ²⁴ , 2 × 10 ²⁴ 1000175Ar Coll He- β 5 × 10 ²³ , 10 ²⁴ , 2 × 10 ²⁴ 1000< | 4 | Be II 3s-3p | 10 ¹⁷ | 5, 15, 50 | _ | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 5 N V 3s-3p 10 ¹⁸ 5, 15, 50 - Model: same as above. 6 Ne VIII 3s-3p 10 ¹⁹ 5, 15, 50 - Model: same as above. 7 Al III 4s-4p 10 ¹⁸ 2, 4, 8 - Model: 4s, 4p, and 4d levels included, no fine structure. Plasma perturbations in two approximations: only electrons and both electrons and ions (AI III). 8 Si XIII $n = 3 \rightarrow 1$ 10 ²¹ , 10 ²² , 10 ²³ 300 - Model: $n = 1$ and 3 singlet levels only, ignoring $\Delta n \neq 0$ interactions. Plasma ions are protons. 9 Al XIII Lyman- α 10 ²¹ , 10 ²² 500 $\omega = 10^{15}$ rad/s, $F = 0, 1, 2$ GV/cm Model: $n = 1$ and 2 levels in two variants: with and without fine structure. Plasma ions are Al XIII, no electrons. 10 D Balmer- α 2 × 10 ¹⁴ , 10 ¹⁵ 1, 5 B = 0, 5, 10 T Model: with/without fine structure for the lower/higher density, respectively; ideal plasma in two variants: ions are either deuterons or infinitely massive particles. 11 D Balmer- β 2 × 10 ¹⁴ , 10 ¹⁵ 1, 5 B = 0, 5, 10 T Model: same as above. 12 D $n = * \rightarrow 2$ 10 ¹⁵ , 10 ¹⁶ , 10 ¹⁷ 1 - Model: fully ionized D plasma, LTE, two variants: only bound-bound transitions included or both bound-bound and free-bound. 13 H Balmer- β 10 ¹⁸ 1 - Model: linear Stark, plasma in two variants: ideal and interacting. Plasma ions: protons. 14 H Balmer- β 10 ¹⁶ 0 - Model: plasma ins are deuterons with 0.1% of Ar XVII. 15 A rXVI He- β $n = 3$ 5 × 10 ²³ , 10 ²⁴ , 2 × 10 ²⁴ 1000 - 15 A rXVI He- β $n = 3$ 5 × 10 ²³ , 10 ²⁴ , 2 × 10 ²⁴ 1000 - 15 A rxvi He- β $n = 4$ 5 × 10 ²³ , 10 ²⁴ , 2 × 10 ²⁴ 1000 - 15 A rxvi He- β $n = 3$ 5 × 10 ²³ , 10 ²⁴ , 2 × 10 ²⁴ 1000 - 15 A rxvi He- β $n = 4$ 5 × 10 ²³ , 10 ²⁴ , 2 × 10 ²⁴ 1000 - 15 A rxvi He- β $n = 4$ 5 × 10 ²³ , 10 ²⁴ , 2 × 10 ²⁴ 1000 - 15 A rxvi He- β $n = 4$ 5 × 10 ²³ , 10 ²⁴ , 2 × 10 ²⁴ 1000 - 15 A rxvi He- β $n = 4$ 5 × 10 ²³ , 10 ²⁴ , 2 × 10 ²⁴ 1000 - 15 A rxvi He- β $n = 4$ 5 × 10 ²³ , 10 ²⁴ , 2 × 10 ²⁴ 1000 - 15 A rxvi He- β $n = 4$ 5 × 10 ²³ , 10 ²⁴ , 2 × 10 ²⁴ 1000 - 15 A rxvi He- β $n = 4$ 5 × 10 ²³ , 10 ²⁴ , 2 × 10 ²⁴ 1000 | | Model: 3s 3n and 3d levels included no fine structure. Only electron broadening included in two approximations: straight paths and hyperbolic trajectories | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Model: same as above. 10^{19} $5, 15, 50$ $-$ 6Ne VIII $3s-3p$ 10^{18} $2, 4, 8$ $-$ 7Al III $4s-4p$ 10^{18} $2, 4, 8$ $-$ 7Al III $4s-4p$ $10^{21}, 10^{22}, 10^{23}$ 300 $-$ Model: $4s, 4p, and 4d$ levels included, no fine structure. Plasma perturbations in two approximations: only electrons and both electrons and ions (Al III).8Si XIII $n = 3 \rightarrow 1$ $10^{21}, 10^{22}$ 300 $-$ Model: $n = 1$ and 3 singlet levels only, ignoring $\Delta n \neq 0$ interactions. Plasma ions are protons. $0 = 10^{15}$ rad/s, $F = 0, 1, 2$ GV/cm9Al XIII Lyman α $0^{21}, 10^{22}$ 500 $\omega = 10^{15}$ rad/s, $F = 0, 1, 2$ GV/cmModel: $n = 1$ and 2 levels in two variants: with and without fine structure. Plasma ions are Al XIII, no electrons. $0 = 10^{15}$ rad/s, $F = 0, 1, 2$ GV/cm10D Balmer $-\alpha$ $2 \times 10^{14}, 10^{15}$ $1, 5$ $B = 0, 5, 10$ TModel: with/without fine structure for the lower/higher density, respectively; ideal plasma in two variants: ions are either deuterons or infinitelymassive particles. $1, 5$ $B = 0, 5, 10$ T11D Balmer $-\beta$ $2 \times 10^{14}, 10^{15}$ $1, 5$ 2 $D n = * - 2$ $10^{15}, 10^{16}, 10^{17}$ 1 3H Balmer $-\alpha$ 10^{18} 1 4H Balmer $-\beta$ 10^{18} 1 5Ar XVII Her $-\beta$ $5 \times 10^{23}, 10^{24}, 2 \times 10^{24}$ 1000 6Ar XVII Her $-\beta$ $5 \times 10^{23}, 10^{24}, 2 \times 10^{24}$ 1000 7Ar XVII Her $-\beta$ | 5 | N V $3s-3p$ | 10 ¹⁸ | 5. 15. 50 | - | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 6Ne VIII 3s-3p10195, 15, 50-Model: same as above.2, 4, 8-7AI III 4s-4p10182, 4, 8-Model: 4s, 4p, and 4d levels included, no fine structure. Plasma perturbations in two approximations: only electrons and both electrons and ions (AI III).8Si XII n = 3 → 1102 ¹ , 102 ² , 10 ²³ 300-Model: n = 1 and 3 single levels only, ignoring Δn ≠ 0 interactions. Plasma ions are protons.9AI XIII Lyman-α10 ²¹ , 10 ²² 500ω = 1015 rad/s, F = 0, 1, 2 GV/cmModel: n = 1 and 2 levels in two variants: with and without fine structure. Plasma ions are AI XIII, no electrons.B = 0, 5, 10 TModel: same as above.3 × 10 ¹⁴ , 10 ¹⁵ 1, 5B = 0, 5, 10 TModel: same as above.10 ¹⁶ , 10 ¹⁷ 1-12D n = * → 210 ¹⁵ , 10 ¹⁶ , 10 ¹⁷ 1-Model: fully ionized D plasma, LTE, two variants: only bound-bound transitions included or both bound-bound and free-bound.113H Balmer-α10 ¹⁸ 1-Model: same as above14H Balmer-β10 ¹⁶ 1-Model: same as above15Ar XVI He-β5 × 10 ²³ , 10 ²⁴ , 2 × 10 ²⁴ 1000-15aAr XVI He-β5 × 10 ²³ , 10 ²⁴ , 2 × 10 ²⁴ 1000-15bAr XVI He-β ⁶ n = 35 × 10 ²³ , 10 ²⁴ , 2 × 10 ²⁴ 1000-15aAr XVI He-β ⁶ n = 45 × 10 ²³ , 10 ²⁴ , 2 × 10 ²⁴ 1000-15aAr XVI He-β ⁶ n = 45 × | | Model: same as above. | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Model: same as above.7Al III 4s-4p 10^{18} 2, 4, 8-Model: 4s, 4p, and 4d levels included, no fine structure. Plasma perturbations in two approximations: only electrons and both electrons and ions (Al III).Si XIII n = 3 \rightarrow 1 10^{21} , 10^{22} , 10^{23} 300-Model: n = 1 and 3 singlet levels only, ignoring $\Delta n \neq 0$ interactions. Plasma ions are protons.9 $\omega = 10^{15} \operatorname{rad/s}, F = 0, 1, 2 \operatorname{GV/cm}$ Model: n = 1 and 2 levels in two variants: with and without fine structure. Plasma ions are Al XIII, no electrons.10 $\omega = 10^{15} \operatorname{rad/s}, F = 0, 1, 2 \operatorname{GV/cm}$ Model: with/without fine structure for the lower/higher density, respectively; ideal plasma in two variants: ions are either deuterons or infinitely massive particles.10D Balmer- β $2 \times 10^{14}, 10^{15}$ $1, 5$ $B = 0, 5, 10 \operatorname{T}$ 11D Balmer- β $2 \times 10^{14}, 10^{15}$ $1, 5$ $B = 0, 5, 10 \operatorname{T}$ 12D n = * $\rightarrow 2$ $10^{15}, 10^{16}, 10^{17}$ 1 $-$ Model: fully ionized D plasma, LTE, two variants: ionly bound-bound transitions included or both bound-bound and free-bound.13H Balmer- β 10^{18} 1 14H Balmer- β $5 \times 10^{23}, 10^{24}, 2 \times 10^{24}$ 1000 15Ar XVII He- β $5 \times 10^{23}, 10^{24}, 2 \times 10^{24}$ 1000 15Ar XVII He- β n = 2 $5 \times 10^{23}, 10^{24}, 2 \times 10^{24}$ 1000 15Ar XVII He- β n = 3 $5 \times 10^{23}, 10^{24}, 2 \times 10^{24}$ 1000 15Ar XVII He- β n = 4 $5 \times 10^{23}, 10^{24}, 2 \times 10^{24}$ 1000 15 <td>6</td> <td>Ne VIII 3s–3p</td> <td>10¹⁹</td> <td>5. 15. 50</td> <td>_</td> | 6 | Ne VIII 3s–3p | 10 ¹⁹ | 5. 15. 50 | _ | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 7Al III 4s-4p10182, 4, 8-Model: 4s, 4p, and 4d levels included, no fine structure. Plasma perturbations in two approximations: only electrons and both electrons and ions (AI III).8Si XIII n = 3 → 110 ²¹ , 10 ²² , 10 ²³ 300-Model: n = 1 and 3 singlet levels only, ignoring An ≠ 0 interactions. Plasma ions are protons.9Al XIII Lyman-α10 ²¹ , 10 ²² 500ω = 1015 rad/s, F = 0, 1, 2 GV/cmModel: n = 1 and 2 levels in two variants: with and without fine structure. Plasma ions are Al XIII, no electrons.DBalmer-α2 × 1014, 10151, 5B = 0, 5, 10 TModel: with/without fine structure for the lower/higher density, respectively; ideal plasma in two variants: ions are either deuterons or infinitely massive particles.Nodel: n = 1n = 0, 5, 10 T10D Balmer-β2 × 10 ¹⁴ , 10 ¹⁵ 1, 5B = 0, 5, 10 TModel: fully ionized D plasma, LTE, two variants: only bound-bound transitions included or both bound-bound and free-bound.113H Balmer-β10 ¹⁵ , 10 ¹⁶ , 10 ¹⁷ 114H Balmer-β10 ¹⁸ 115Ar XVII He-β5 × 10 ²³ , 10 ²⁴ , 2 × 10 ²⁴ 161-Model: same as above15Ar XVII He-β5 × 10 ²³ , 10 ²⁴ , 2 × 10 ²⁴ 161-175 × 10 ²³ , 10 ²⁴ , 2 × 10 ²⁴ 18arx VII He-β1195 × 10 ²³ , 10 ²⁴ , 2 × 10 ²⁴ 1000-15Ar XVI He-β ⁿ n = 25 × 10 ²³ , 10 ²⁴ , 2 × 10 ²⁴ 1000-< | | Model: same as above. | | -,, | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Model: 4s, 4p, and 4d levels included, no fine structure. Plasma perturbations in two approximations: only electrons and both electrons and ions (AI III).8Si XIII $n = 3 \rightarrow 1$ $10^{21}, 10^{22}, 10^{23}$ 300 $-$ Model: $n = 1$ and 3 singlet levels only, ignoring $\Delta n \neq 0$ interactions. Plasma ions are protons. $= 10^{15}$ rad/s, $F = 0, 1, 2$ GV/cm9Al XIII Lyman- α $10^{21}, 10^{22}$ 500 $\omega = 10^{15}$ rad/s, $F = 0, 1, 2$ GV/cmModel: $n = 1$ and 2 levels in two variants: with and without fine structure. Plasma ions are Al XIII, no electrons. D 10D Balmer- α $2 \times 10^{14}, 10^{15}$ $1, 5$ $B = 0, 5, 10$ TModel: with/without fine structure for the lower/higher density, respectively; ideal plasma in two variants: ions are either deuterons or infinitely massive particles.11D Balmer- β $2 \times 10^{14}, 10^{15}$ $1, 5$ 12 $D n = ^* \rightarrow 2$ $10^{15}, 10^{16}, 10^{17}$ 1 13H Balmer- α 10^{18} 1 14H Balmer- α 10^{18} 1 15Ar XVII He- β $5 \times 10^{22}, 10^{24}, 2 \times 10^{24}$ 1000 15Ar XVII He- β $5 \times 10^{22}, 10^{24}, 2 \times 10^{24}$ 1000 15Ar XVII He- β $n = 4$ $5 \times 10^{23}, 10^{24}, 2 \times 10^{24}$ 1000 15Ar XVII He- β $n = 4$ $5 \times 10^{23}, 10^{24}, 2 \times 10^{24}$ 1000 15Ar XVI He- β $n = 4$ $5 \times 10^{23}, 10^{24}, 2 \times 10^{24}$ 1000 15Ar XVI He- β $n = 4$ $5 \times 10^{23}, 10^{24}, 2 \times 10^{24}$ 1000 15A | 7 | Al III $4s - 4p$ | 10 ¹⁸ | 2, 4, 8 | _ | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 8 Si XIII $n = 3 \rightarrow 1$ $10^{21}, 10^{22}, 10^{23}$ 300 – Model: $n = 1$ and 3 singlet levels only, ignoring $\Delta n \neq 0$ interactions. Plasma ions are protons. 9 Al XIII Lyman- α $10^{21}, 10^{22}$ 500 $\omega = 10^{15}$ rad/s, $F = 0, 1, 2$ GV/cm Model: $n = 1$ and 2 levels in two variants: with and without fine structure. Plasma ions are Al XIII, no electrons. 1 D Balmer- α $2 \times 10^{14}, 10^{15}$ $1, 5$ $B = 0, 5, 10$ T Model: with/without fine structure for the lower/higher density, respectively; ideal plasma in two variants: ions are either deuterons or infinitely massive particles. 11 D Balmer- β $2 \times 10^{14}, 10^{15}$ $1, 5$ $B = 0, 5, 10$ T Model: same as above. 12 D $n = * \rightarrow 2$ $10^{15}, 10^{16}, 10^{17}$ 1 — Model: fully ionized D plasma, LTE, two variants: only bound-bound transitions included or both bound-bound and free-bound. 13 H Balmer- α 10^{18} 1 — Model: linear Stark, plasma in two variants: ideal and interacting. Plasma ions: protons. 14 H Balmer- β $5 \times 10^{23}, 10^{24}, 2 \times 10^{24}$ 1000 — Model: same as above. 15 Ar XVII He- β^* $n = 2$ $5 \times 10^{23}, 10^{24}, 2 \times 10^{24}$ 1000 — Model: plasma ions are deuterons with 0.1% of Ar XVII. 15 Ar XVII He- β^* $n = 3$ $5 \times 10^{23}, 10^{24}, 2 \times 10^{24}$ 1000 — Model: plasma ions are deuterons with 0.1% of Ar XVII. | | Model: 4s, 4p, and 4d levels included, no fine structure. Plasma perturbations in two approximations: only electrons and both electrons and ions (Al III). | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Model: $n = 1$ and 3 singlet levels only, ignoring $\Delta n \neq 0$ interactions. Plasma ions are protons.9Al XIII Lyman- α 10^{21} , 10^{22} 500 $\omega = 10^{15}$ rad/s, $F = 0, 1, 2$ GV/cmModel: $n = 1$ and 2 levels in two variants: with and without fine structure. Plasma ions are Al XIII, no electrons. $B = 0, 5, 10$ T10D Balmer- α $2 \times 10^{14}, 10^{15}$ $1, 5$ $B = 0, 5, 10$ TModel: with/without fine structure for the lower/higher density, respectively; ideal plasma in two variants: ions are either deuterons or infinitely massive particles.11D Balmer- β $2 \times 10^{14}, 10^{15}$ $1, 5$ 12D $n = ^* \rightarrow 2$ $10^{15}, 10^{16}, 10^{17}$ $-$ Model: fully ionized D plasma, LTE, two variants: only bound-bound transitions included or both bound-bound and free-bound.13H Balmer- α 10^{18} $-$ Model: same as above. 10^{18} $-$ Model: same as above. 10^{18} $-$ 14H Balmer- β $5 \times 10^{23}, 10^{24}, 2 \times 10^{24}$ 1000 15Ar XVII He- β $5 \times 10^{23}, 10^{24}, 2 \times 10^{24}$ 1000 15Ar XVII He- β $n = 3$ $5 \times 10^{23}, 10^{24}, 2 \times 10^{24}$ 1000 15Ar XVI He- β $n = 3$ $5 \times 10^{23}, 10^{24}, 2 \times 10^{24}$ 1000 15Ar XVI He- β $n = 4$ $5 \times 10^{23}, 10^{24}, 2 \times 10^{24}$ 1000 15Ar XVI He- β $n = 4$ $5 \times 10^{23}, 10^{24}, 2 \times 10^{24}$ 1000 15Ar XVI He- β $n = 4$ $5 \times 10^{23}, 10^{24}, 2 \times 10^{24}$ 1000 | 8 | Si XIII $n = 3 \rightarrow 1$ | $10^{21}, 10^{22}, 10^{23}$ | 300 | _ | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 9 Al XIII Lyman- α 10 ²¹ , 10 ²² 500 $\omega = 10^{15}$ rad/s, $F = 0, 1, 2$ GV/cm Model: $n = 1$ and 2 levels in two variants: with and without fine structure. Plasma ions are Al XIII, no electrons. 10 D Balmer- α 2 × 10 ¹⁴ , 10 ¹⁵ 1, 5 $B = 0, 5, 10$ T Model: with/without fine structure for the lower/higher density, respectively; ideal plasma in two variants: ions are either deuterons or infinitely massive particles. 11 D Balmer- β 2 × 10 ¹⁴ , 10 ¹⁵ 1, 5 $B = 0, 5, 10$ T Model: same as above. 12 D $n = * \rightarrow 2$ 10 ¹⁵ , 10 ¹⁶ , 10 ¹⁷ 1 - Model: fully ionized D plasma, LTE, two variants: only bound-bound transitions included or both bound-bound and free-bound. 13 H Balmer- α 10 ¹⁸ 1 - Model: linear Stark, plasma in two variants: ideal and interacting. Plasma ions: protons. 14 H Balmer- β 10 ¹⁸ 1 - Model: same as above. 15 Ar XVII He- β 5 × 10 ²³ , 10 ²⁴ , 2 × 10 ²⁴ 1000 - Model: plasma ions are deuterons with 0.1% of Ar XVII. 15 Ar XVI He- β^* $n = 2$ 5 × 10 ²³ , 10 ²⁴ , 2 × 10 ²⁴ 1000 - 15 Ar XVI He- β^* $n = 4$ 5 × 10 ²³ , 10 ²⁴ , 2 × 10 ²⁴ 1000 - 15 Ar XVI He- β^* $n = 4$ 5 × 10 ²³ , 10 ²⁴ , 2 × 10 ²⁴ 1000 - 15 Ar XVI He- β^* $n = 4$ 5 × 10 ²³ , 10 ²⁴ , 2 × 10 ²⁴ 1000 - 15 Ar XVI He- β^* $n = 4$ 5 × 10 ²³ , 10 ²⁴ , 2 × 10 ²⁴ 1000 - 15 Ar XVI He- β^* $n = 4$ 5 × 10 ²³ , 10 ²⁴ , 2 × 10 ²⁴ 1000 - 15 Ar XVI He- β^* $n = 4$ 5 × 10 ²³ , 10 ²⁴ , 2 × 10 ²⁴ 1000 - 15 Ar XVI He- β^* $n = 4$ 5 × 10 ²³ , 10 ²⁴ , 2 × 10 ²⁴ 1000 - 15 Ar XVI He- β^* $n = 4$ 5 × 10 ²³ , 10 ²⁴ , 2 × 10 ²⁴ 1000 - 15 Ar XVI He- β^* $n = 4$ 5 × 10 ²³ , 10 ²⁴ , 2 × 10 ²⁴ 1000 - 15 Ar XVI He- β^* $n = 4$ 5 × 10 ²³ , 10 ²⁴ , 2 × 10 ²⁴ 1000 - 15 Ar XVI He- β^* $n = 4$ 5 × 10 ²³ , 10 ²⁴ , 2 × 10 ²⁴ 1000 - 15 Ar XVI He- β^* $n = 4$ 5 × 10 ²³ , 10 ²⁴ , 2 × 10 ²⁴ 1000 - 15 Ar XVI He- β^* $n = 4$ 5 × 10 ²³ , 10 ²⁴ , 2 × 10 ²⁴ 1000 - 15 Ar XVI He- β^* $n = 4$ 5 × 10 ²³ , 10 ²⁴ , 2 × 10 ²⁴ 1000 - 15 Ar XVI He- β^* $n = 4$ 5 × 10 ²³ , 10 ²⁴ , 2 × 10 ²⁴ 1000 - 15 Ar XVI He- β^* $n = 4$ 5 | | Model: $n = 1$ and 3 singlet levels only ignoring $\Lambda n \neq 0$ interactions. Plasma ions are protons | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Model: <i>n</i> = 1 and 2 levels in two variants: with and without fine structure. Plasma ions are Al XIII, no electrons.10D Balmer-α2 × 10 ¹⁴ , 10 ¹⁵ 1, 5B = 0, 5, 10 TModel: with/without fine structure for the lower/higher density, respectively; ideal plasma in two variants: ions are either deuterons or infinitely massive particles.11D Balmer-β2 × 10 ¹⁴ , 10 ¹⁵ 1, 5B = 0, 5, 10 TModel: same as above.10 ¹⁶ , 10 ¹⁷ 1-12D <i>n</i> = * → 210 ¹⁵ , 10 ¹⁶ , 10 ¹⁷ 1-Model: fully ionized D plasma, LTE, two variants: only bound-bound transitions included or both bound-bound and free-bound.13H Balmer-α10 ¹⁸ 1Model: linear Stark, plasma in two variants: ideal and interacting. Plasma ions: protons.14H Balmer-β10 ¹⁸ 1Model: same as above.115aAr XVII He-β* <i>n</i> = 25 × 10 ²³ , 10 ²⁴ , 2 × 10 ²⁴ 100015bAr XVI He-β* <i>n</i> = 35 × 10 ²³ , 10 ²⁴ , 2 × 10 ²⁴ 100015cAr xvi He-β* <i>n</i> = 45 × 10 ²³ , 10 ²⁴ , 2 × 10 ²⁴ 100015dAr xvi He-β* <i>n</i> = 45 × 10 ²³ , 10 ²⁴ , 2 × 10 ²⁴ 1000 | 9 | Al XIII Lyman-α | 10^{21} , 10^{22} | 500 | $\omega = 10^{15}$ rad/s. $F = 0, 1, 2$ GV/cm | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 10D Balmer- α $2 \times 10^{14}, 10^{15}$ 1, 5 $B = 0, 5, 10 \text{ T}$ Model: with/without fine structure for the lower/higher density, respectively; ideal plasma in two variants: ions are either deuterons or infinitely massive particles.11D Balmer- β $2 \times 10^{14}, 10^{15}$ 1, 5 $B = 0, 5, 10 \text{ T}$ Model: same as above.1-12D $n = * \rightarrow 2$ $10^{15}, 10^{16}, 10^{17}$ 1-Model: fully ionized D plasma, LTE, two variants: only bound-bound transitions included or both bound-bound and free-bound.13H Balmer- α 10^{18} 1-Model: linear Stark, plasma in two variants: ideal and interacting. Plasma ions: protons14H Balmer- β 10^{18} 1-Model: same as above15aAr XVII He- β $5 \times 10^{23}, 10^{24}, 2 \times 10^{24}$ 1000-15bAr XVII He- β^* $n = 2$ $5 \times 10^{23}, 10^{24}, 2 \times 10^{24}$ 1000-15cAr xvi He- β^* $n = 4$ $5 \times 10^{23}, 10^{24}, 2 \times 10^{24}$ 1000-15dAr xvi He- β^* $n = 4$ $5 \times 10^{23}, 10^{24}, 2 \times 10^{24}$ 1000-15dAr xvi He- β^* $n = 4$ $5 \times 10^{23}, 10^{24}, 2 \times 10^{24}$ 1000-15dAr xvi He- β^* $n = 4$ $5 \times 10^{23}, 10^{24}, 2 \times 10^{24}$ 1000-15dAr xvi He- β^* $n = 4$ $5 \times 10^{23}, 10^{24}, 2 \times 10^{24}$ 1000-15dAr xvi He- β^* $n = 4$ $5 \times 10^{23}, 10^{24}, 2 \times 10^{24}$ 1000-15dAr xvi He- β^* | | Model: $n = 1$ and 2 levels in two var | iants: with and without fine structure. Plas | ma ions are Al XIII, no electro | ons. | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Model: with/without fine structure for the lower/higher density, respectively; ideal plasma in two variants: ions are either deuterons or infinitely massive particles.11D Balmer- β $2 \times 10^{14}, 10^{15}$ 1, 5 $B = 0, 5, 10 \text{T}$ 12D $n = * \rightarrow 2$ $10^{15}, 10^{16}, 10^{17}$ 1 $-$ Model: same as above. 1 $-$ 13H Balmer- α 10^{18} 1 $-$ Model: linear Stark, plasma in two variants: ideal and interacting. Plasma ions: protons. $-$ 14H Balmer- β 10^{18} 1 $-$ Model: same as above. $ -$ 15aAr XVII He- β $5 \times 10^{23}, 10^{24}, 2 \times 10^{24}$ 1000 $-$ 15bAr XVI He- β^* $n = 2$ $5 \times 10^{23}, 10^{24}, 2 \times 10^{24}$ 1000 $-$ 15cAr xvI He- β^* $n = 4$ $5 \times 10^{23}, 10^{24}, 2 \times 10^{24}$ 1000 $-$ 15cAr xvI He- β^* $n = 4$ $5 \times 10^{23}, 10^{24}, 2 \times 10^{24}$ 1000 $-$ 15cAr xvI He- β^* $n = 4$ $5 \times 10^{23}, 10^{24}, 2 \times 10^{24}$ 1000 $-$ 15dAr xvI He- β^* $n = 4$ $5 \times 10^{23}, 10^{24}, 2 \times 10^{24}$ 1000 $-$ 15cAr xvI He- β^* $n = 4$ $5 \times 10^{23}, 10^{24}, 2 \times 10^{24}$ 1000 $-$ 15dAr xvI He- β^* $n = 4$ $5 \times 10^{23}, 10^{24}, 2 \times 10^{24}$ 1000 $-$ 15dAr xvI He- β^* $n = 4$ $5 \times 10^{23}, 10^{24}, 2 \times 10^{24}$ 1000 $-$ 15dAr xvI He- β^* $n = 4$ $5 \times 10^{23}, 10^{24}, 2 \times 10^{24}$ 1000 $-$ | 10 | D Balmer- α | $2 \times 10^{14}, 10^{15}$ | 1.5 | B = 0.5.10 T | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| massive particles.1D1111DBalmer-β2 × 10 ¹⁴ , 10 ¹⁵ 1, 5B = 0, 5, 10 TModel: same as above.112D $n = * \rightarrow 2$ 10 ¹⁵ , 10 ¹⁶ , 10 ¹⁷ 1-Model: fully ionized D plasma, LTE, two variants: only bound-bound transitions included or both bound-bound and free-bound.13H Balmer-α10 ¹⁸ 1-Model: linear Stark, plasma in two variants: ideal and interacting. Plasma ions: protons14H Balmer-β10 ¹⁸ 1-Model: same as above15aAr XVII He-β5 × 10 ²³ , 10 ²⁴ , 2 × 10 ²⁴ 1000-15bAr XVI He-β* n = 25 × 10 ²³ , 10 ²⁴ , 2 × 10 ²⁴ 1000-15cAr xvi He-β* n = 35 × 10 ²³ , 10 ²⁴ , 2 × 10 ²⁴ 1000-15dAr xvi He-β* n = 45 × 10 ²³ , 10 ²⁴ , 2 × 10 ²⁴ 1000-15dAr xvi He-β* n = 45 × 10 ²³ , 10 ²⁴ , 2 × 10 ²⁴ 1000-15dAr xvi He-β* n = 45 × 10 ²³ , 10 ²⁴ , 2 × 10 ²⁴ 1000-15dAr xvi He-β* n = 45 × 10 ²³ , 10 ²⁴ , 2 × 10 ²⁴ 1000-15dAr xvi He-β* n = 45 × 10 ²³ , 10 ²⁴ , 2 × 10 ²⁴ 1000-15dAr xvi He-β* n = 45 × 10 ²³ , 10 ²⁴ , 2 × 10 ²⁴ 1000-15dAr xvi He-β* n = 45 × 10 ²³ , 10 ²⁴ , 2 × 10 ²⁴ 1000-15dAr xvi He-β* n = 45 × 10 ²³ , 10 ²⁴ , 2 × 10 ²⁴ 1000-< | | Model: with/without fine structure for | or the lower/higher density, respectively; id | leal plasma in two variants: i | ons are either deuterons or infinitely | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
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| Model: same as above.12 $D n = * \rightarrow 2$ $10^{15}, 10^{16}, 10^{17}$ 113H Balmer- α 10^{18} 114H Balmer- α 10^{18} 115Ar XVII He- β 10^{18} 115aAr XVII He- β $5 \times 10^{23}, 10^{24}, 2 \times 10^{24}$ 1000 15bAr XVI He- $\beta^* n = 2$ $5 \times 10^{23}, 10^{24}, 2 \times 10^{24}$ 1000 15cAr xvi He- $\beta^* n = 4$ $5 \times 10^{23}, 10^{24}, 2 \times 10^{24}$ 1000 15cAr xvi He- $\beta^* n = 4$ $5 \times 10^{23}, 10^{24}, 2 \times 10^{24}$ 1000 15dAr xvi He- $\beta^* n = 4$ $5 \times 10^{23}, 10^{24}, 2 \times 10^{24}$ 1000 15dAr xvi He- $\beta^* n = 4$ $5 \times 10^{23}, 10^{24}, 2 \times 10^{24}$ 1000 15dAr xvi He- $\beta^* n = 4$ $5 \times 10^{23}, 10^{24}, 2 \times 10^{24}$ 1000 | 11 | D Balmer- β | 2×10^{14} , 10^{15} | 1.5 | B = 0.5, 10 T | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
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| 12 | $D n = * \rightarrow 2$ | $10^{15}, 10^{16}, 10^{17}$ | 1 | _ | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
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| Atomic model, with and without the interference term in the electron broadening, plasma model, as above, | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |

corresponding models are purposefully made simple: 1) we assume an ideal plasma which for the line broadening calculations will mean straight path trajectories and infinite Debye length for molecular dynamics (MD) simulations, or a Holtsmark distribution for analytical approaches and 2) pure linear Stark effect so that interactions between states with $\Delta n \neq 0$ are ignored and no fine structure is included. In order to assess the influence of electrons and ions, which are protons for the reference cases, the broadening was calculated assuming the electrons and protons act separately and together, so that there are three variants in total for each pair of n_e and T.

2.2. High-n $\Delta n = 1$ transitions

3. Hydrogen $n = 6 \rightarrow n = 5$ transition. This case was calculated using three atomic models: (i) no $\Delta n \neq 0$ coupling accounted for, (ii) n = 5 and n = 6 states couple, and (iii) n = 5, 6, and 7 states included in the Hamiltonian and allowed to mix.

This line is a representative of $n, n' \gg 1, \Delta n \ll n$ class of transitions that includes the radio-frequency lines, which are of great interest for astrophysics. However, due to the computational costs, an n was chosen that is not sufficiently high to be categorized as a radio-frequency transition. Nevertheless, the couplings between states with $\Delta n \neq 0$ were important.

2.3. Isolated lines

First, three species from the Li-like 3s-3p sequence were chosen, for which the divergence between quantum mechanical (QM) calculations and experiments grows with Z [6]:

- 4. Be II is the first non-neutral species of the sequence.
- 5. N V an intermediate *Z*.
- 6. Ne VIII is about the highest *Z* for which the 3s-3p broadening can be reliably measured.

The plasma model for these cases included only electrons, and it was assumed that they move either along straight path trajectories or the more realistic quasi-classical hyperbolic trajectories (due to the Coulomb interaction with the radiator) in order to investigate this effect.

In addition, another isolated line was considered for which quantum effects are not expected to be so significant (i.e., larger matrix elements and cross-sections):

- 7. Al III 4*s*–4*p*. In addition to the width, values of the line shift were compared.
- 2.4. Intermediate case between isolated and degenerate regimes
- 8. He-like Si XIII $3 \rightarrow 1$ transitions without inter-combination lines. At the lower density, only 1s-3p (He- β proper) is seen, then 1s-3d and 1s-3s appear as well, approaching Lyman- β -like shape at the highest density. Plasma ions are protons.

2.5. External fields

9. Al XIII Lyman- α under external harmonic perturbation, e.g., a laser. The functional dependence of the electric field is $Fcos(\omega t)$, with ω and F given in Table 1. The two plasma densities correspond to laser-dominated and plasma-dominated line

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