Line shape models in magnetic fusion research and astrophysics

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Outline

1) Presentation of tokamak plasmas

2) Passive spectroscopy modeling: line shapes, Stark broadening, and Zeeman effect

3) Applying line shape models to stellar atmosphere spectra analysis
Presentation of tokamak plasmas

Center:
- $T_e, T_i$ up to 10 keV
- fully ionized H plasma
- presence of multicharged impurity ions

Electron densities range in $\sim 10^{12} - 10^{15}$ cm$^{-3}$
B-field: several teslas

Edge & divertor:
- temperatures down to 1 eV, and less
- a large amount of neutrals can be present ("detached regime")
- strong atomic line radiation
An extensive set of diagnostics

See Progress in the ITER Physics Basis, Nucl. Fusion special issue (2007)

Spectroscopic observations are done in a wide wavelength range: IR, visible, X... Passive and active methods are used.
An extensive set of diagnostics

<table>
<thead>
<tr>
<th>Spectral Region</th>
<th>Wavelength/Energy Region</th>
</tr>
</thead>
<tbody>
<tr>
<td>Near infrared</td>
<td>700 to 1200 nm / 1 to 2 eV</td>
</tr>
<tr>
<td>Visible</td>
<td>400 to 700 nm / 2 to 3 eV</td>
</tr>
<tr>
<td>Ultraviolet</td>
<td>200 to 400 nm / 3 to 6 eV</td>
</tr>
<tr>
<td>Vacuum ultraviolet</td>
<td>30 to 200 nm / 6 to 40 eV</td>
</tr>
<tr>
<td>Extreme ultraviolet</td>
<td>10 to 30 nm / 40 to 120 eV</td>
</tr>
<tr>
<td>Soft X-ray</td>
<td>0.1 to 10 nm / 120 to 12000 eV</td>
</tr>
</tbody>
</table>
Passive spectroscopy in current tokamaks

An analysis of line shapes, line widths, line intensities provides information on the plasma parameters.

All elements are considered:
- neutral atoms and molecules (edge region, divertor)
- multicharged impurity ions (core region)
Hydrogen line spectra in tokamak edge and divertor plasmas

**JET (EU)**

Koubiti et al., JQSRT (2003)

**Alcator C-Mod (US)**

Welch et al., PoP (1995)

**ASDEX Upgrade (Germany)**

Wenzel et al., Nucl. Fusion (1999)

**JT-60U (Japan)**

Kubo et al., PPCF (1998)
An example of diagnostic: Balmer $\alpha$ ($n = 3 \rightarrow 2$) line shape analysis

Relevant line broadening mechanisms: Zeeman & Doppler effects
Inferring information on the plasma recycling at the edge

The shape of the Zeeman components reflects the neutral velocity distribution function $f(v)$

Example: TEXTOR (Germany)
Stark broadening on high-n Balmer lines

In a plasma, the microscopic electric field perturbs the energy levels

\[ E = 0 \quad E \neq 0 \]

The Hamiltonian \(-d.E\) scales as \(n^2\)

Lines with a high principal quantum number are affected by Stark broadening.
Density estimates from high-n series observed in recombining divertor plasmas

Example: JET
M. Koubiti et al., JQSRT 81, 265 (2003)

\[ N_e \sim 10^{14} \text{ cm}^{-3} \]
Stark broadening modeling

When emitting or absorbing a photon, an atom feels the presence of the charged particles located at vicinity

A Stark broadened line is proportional to the Fourier transform of the atomic dipole autocorrelation function

\[ I(\omega) \propto \frac{1}{\pi} \text{Re} \int_0^\infty \left\langle \vec{d}(0) \cdot \vec{d}(t) \right\rangle e^{i\omega t} dt \]
Calculation methods

Many models, formulas and codes have been developed:
- quasistatic approximation (-d.E = cst)
- kinetic theory
- collision operators
- stochastic processes (MMM, FFM)
- fully numerical simulations

They are complementary to each other

Their validity can be assessed through comparisons to experimental spectra, and by cross-checking between codes
Ion dynamics effects on low-n lines

Dγ line (deuterium Balmer γ)

The ion dynamics yields additional broadening
Adapting the line shape models to stellar atmospheres

In stellar atmospheres, the temperature is low enough so that there is a significant amount of neutrals.

The spectrum of A type stars presents hydrogen absorption lines which can be analyzed using the same tools as in magnetic fusion.

http://vizier.u-strasbg.fr/viz-bin/VizieR
Stark broadening in stellar atmosphere conditions

\[ \Delta \omega \] (eV)

\[ H_\alpha \]

\[ N_e = 10^{17} \text{ cm}^{-3} \]

\[ T = 1 \text{ eV} \]
A value of 360 T was inferred for B from the separation between the Zeeman components.
Observation of asymmetric Zeeman triplets

SDSS database

Hα Zeeman components
At very strong magnetic fields, a term proportional to $B^2$ must be retained in the Hamiltonian

$$\frac{1}{2m_e} (\vec{p} + e\vec{A})^2 = \frac{p^2}{2m_e} - \vec{\mu} \cdot \vec{B} + \frac{e^2 \vec{A}^2}{2m_e}$$

**Atomic physics with quadratic Zeeman effect**

linear Zeeman effect

quadratic Zeeman effect
Quadratic Zeeman effect

\[ \Delta \omega (\text{eV}) \]

Normalized line shape

- \( H_\alpha \)
- \( N_\text{e} = 10^{17} \text{ cm}^{-3} \)
- \( T_\text{e} = T_\text{i} = 1 \text{ eV} \)
- \( B = 2000 \text{ T} \)
- \( \theta = 90^\circ \)
Quadratic Zeeman effect

- $H\beta$
- $N_e = 10^{17} \text{ cm}^{-3}$
- $T_e = T_i = 1 \text{ eV}$
- $B = 2000 \text{ T}$
- $\theta = 90^\circ$
1) Atomic spectroscopy can be used as a diagnostic for tokamak edge and divertor plasmas. Models involve both atomic and plasma physics.

2) A problem inherent to hydrogen line shape modeling concerns the description of Stark broadening.

3) Models can be applied both to magnetic fusion and astrophysics.