X-RAY POWERFUL DIAGNOSTICS FOR HIGHLY-IONIZED PLASMAS: HE-LIKE IONS

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ABSTRACT

The calculations of the ratios of the Helium-like ion X-ray lines from C\textsubscript{V} to Si\textsubscript{xiii} are revisited in order to apply the results to density, temperature and ionization process diagnostics of data from high-resolution spectroscopy of the new generation of X-ray satellites: Chandra and XMM-Newton. Comparing to earlier computations, Porquet & Dubau (2000), the best experimental values are used for radiative transition probabilities. The influence of an external radiation field (photo-excitation), the contribution from unresolved dielectronic satellite lines and the optical depth are taken into account. These diagnostics could be applied to collision-dominated plasmas (e.g., stellar coronae), photo-ionized plasmas (e.g., “Warm Absorber” in AGNs), and transient plasmas (e.g., SNRs).

Key words: atomic data – atomic process – line: formation – techniques: spectroscopic – X-rays

1. INTRODUCTION

With the advent of a new generation of X-ray satellites (Chandra and XMM-Newton), X-ray spectroscopy for extra-solars objects with unprecedented spectral resolution and high S/N is now possible for the first time. Various plasma diagnostics are accessible such as those based on the line ratios of He-like ions. The wavelength ranges of the RGS (6-35 Å), of the LETGS (2-175 Å), and of the HETGS (MEG range: 2.5-31 Å; HEG range: 1.2-15 Å) contain the Helium-like line ”triplets” from C\textsubscript{V} (or N\textsubscript{v}1 for the RGS, and for the HETGS-HEG) to Si\textsubscript{xiii} (Table \ref{tab:line_ratios}). The ratios of these lines was already widely used for solar plasma diagnostics (e.g., Mewe &Schrijver 1978\textsuperscript{a}, 1978\textsuperscript{b}; Doyle 1980; Pradhan & Shull 1981).

The analysis of the He-like “triplet” is a powerful tool in the analysis of the high-resolution spectra of a variety of plasmas such as:

- collisional plasmas: e.g., stellar coronae (OB stars, late type stars, active stars, ...)
- photo-ionized or hybrid plasmas (photo-ionization + collisional ionization): e.g., “Warm Absorber” (in AGNs), X-ray binaries, ...
- out of equilibrium plasmas: e.g., SNRs, ...

Figure 1. Simplified level scheme for Helium-like ions. w (or r), x,y (or i), and z (or f): resonance, intercombination, and forbidden lines, respectively. Full upward arrows: collisional excitation transitions, broken arrows: radiative transitions (including photo-excitation from 2\textsuperscript{3}S\textsubscript{1} to 2\textsuperscript{3}P\textsubscript{1,2} levels, and 2-photon continuum from 2\textsuperscript{1}S\textsubscript{0} to the ground level), and thick skew arrows: recombination (radiative and dielectronic) plus cascade processes.

2. DIAGNOSTICS

In the X-ray range, the three most intense lines of Helium-like ions (“triplet”) are: the resonance line (w, also called r: 1s\textsuperscript{2}1S\textsubscript{0} – 1s2p\textsuperscript{1}P\textsubscript{1}), the intercombination line (x+y, also called i: 1s\textsuperscript{2}1S\textsubscript{0} – 1s2p\textsuperscript{3}P\textsubscript{2,1}) and the forbidden line (z, also called f: 1s\textsuperscript{2}1S\textsubscript{0} – 1s2s\textsuperscript{3}S\textsubscript{1}). They correspond to transitions between the n=2 shell and the n=1 ground-state shell (see Figure 1).

Gabriel & Jordan (1969) introduced the techniques to determine, from the ratios R and G, electron density and temperature of the Solar corona:

\[ R(n_e) = \frac{z}{(x+y)} \quad G(T_e) = \frac{(x+y)+z}{w} \quad (1) \]

2.1. DENSITY DIAGNOSTIC

In the low-density limit, all n=2 states are populated directly or via upper-level radiative cascades by electron impact from the He-like ground state and/or by (radiative and dielectronic) recombination of H-like ions (see Fig-
2.2. Temperature and ionization process diagnostics

The ratio \( G \) (see Eq. [1]) is sensitive to the electron temperature since the collisional excitation rates have not the same dependence with temperature for the resonance line as for the forbidden and intercombination lines.

In addition, as detailed in Porquet & Dubau [2000] (see also Mewe [1999] and Liedahl [1999]), the relative intensity of the resonance \( w \) line, compared to the forbidden \( z \) and the intercombination \( x+y \) lines, contains information about the ionization processes that occur: a strong resonance line compared to the forbidden or the intercombination lines corresponds to collision-dominated plasmas. It leads to a ratio of \( G = ((x+y)+z)/w \sim 1 \). On the contrary, a weak resonance line corresponds to plasmas dominated by the photo-ionization \( G = (x+y+z)/w > 4 \). An illustration is given Figure 2.

However, as mentioned for the density diagnostic, caution should be taken since photo-excitation can mimic a hybrid plasmas, i.e. photo-ionization plus collisional ionization, e.g. shock or starburst (see §5.2).

3. Blended dielectronic satellite lines

The influence of the blending of dielectronic satellite lines for the resonance, the intercombination and the forbidden lines has been taken into account when their contribution is not negligible in the calculation of \( R \) and \( G \), affecting the inferred electron temperature and density. This is the case for the high-Z ions produced in a collisional plasma, i.e. Ne IX, Mg XI, and Si XIII (Z=10, 12, and 14, respectively).

\[
R = \frac{z + satz}{(x+y) + satxy}
\]

\[G = \frac{(z + satz) + ((x+y) + satxy)}{(w + satw)},\]
where \( satz \), \( satxy \) and \( satz \) are respectively the contribution of blended dielectronic satellite lines to the forbidden line, to the intercombination lines, and to the resonance line, respectively. One can note that at very high density the \( ^3P \) levels are depleted to the \( ^1P \) level, and in that case \( x+y \) decreases and \( R \) tends to \( satz/satxy \).

The intensity of a dielectronic satellite line arising from a doubly excited state with principal quantum number \( n \) in a Lithium-like ion produced by dielectronic recombination of a He-like ion is given by:

\[
I_s = N_{He} n_e C_s, \tag{4}
\]

where \( N_{He} \) is the population density of the considered He-like ion in the ground state 1s\(^2\) with statistical weight \( g_1 \) (for He-like ions \( g_1 = 1 \)).

The rate coefficient (in \( \text{cm}^3\text{s}^{-1} \)) for dielectronic recombination is given by (Bely-Dubau et al. 1979):

\[
C_s = 2.0706 \times 10^{-10} \frac{e^{-E_s/kT_e}}{g_1 T_e^{3/2}} F_2(s), \tag{5}
\]

where \( E_s \) is the upper energy level of the satellite line \( s \) with statistical weight \( g_s \) above the ground state 1s\(^2\) of the He-like ion. \( T_e \) is the electron temperature in K, and \( F_2(s) \) is the so-called line strength factor (often of the order of about \( 10^{13} \) \( \text{s}^{-1} \) for the stronger lines) given by

\[
F_2(s) = \frac{g_s A_s A_r}{(A_a + \sum A_r)}, \tag{6}
\]

where \( A_a \) and \( A_r \) are transition probabilities \( \text{s}^{-1} \) by auto-ionization and radiation, and the summation is over all possible radiative transitions from the satellite level \( s \).

Since the contribution of the blended dielectronic satellite lines depends on the spectral resolution considered, we have estimated the ratios \( R \) and \( G \) for four specific spectral resolutions (FWHM): RGS-1 at the first order, LETGS, HETGS-MEG, and HETGS-HEG (Porquet, Mewe et al. 2001). At the temperature at which the ion fraction is maximum for the He-like ion (see e.g. Mazzotta et al. 1998), the differences between the calculations for \( R \) (for \( G \)) with or without taking into account the blended dielectronic satellite lines are only of about 1% (9%), 2% (5%), and 5% (3%) for \( \text{Ne}^{10} \), \( \text{Mg}^{11} \), and \( \text{Si}^{13} \) at the low-density limit and for \( T_{rad} = 0 \) K, respectively.

However, for photo-ionized plasmas where recombination prevails and the temperature is much lower (e.g., \( T \lesssim 0.1 T_m \)), the effect on \( R \) and \( G \) can be much bigger since \( I_{sat}/I_w \propto T^{-1} e^{-E_{sat}/kT} \). For very high density \( n_e \) the contribution of the blended dielectronic satellite lines to the forbidden line leads to a ratio \( R \) which tends to \( satz/satxy \), hence decreases much slower with \( n_e \) than in the case where the contribution of the blended DR satellites is not taken into account.

### 4. Optical Depth

If the optical depth of the resonance line is not taken into account, the calculated ratio \( G \) could be overestimated (inferred temperature underestimated) when the optically-thin approximation is no longer valid. This has been estimated with an escape-factor method, e.g., for the case of a Warm Absorber in an AGNs (Porquet, Kaastra, Mewe, Dubau 2002).

### 5. Radiation Field (Photo-excitation)

#### 5.1. Influence on Density Diagnostic

A strong radiation field can mimic a high density if the photo-excitation \( ^3S_1 \) level (f line) \( \rightarrow ^3P_{0,1,2} \) levels (f lines) exceeds the electron collisional excitation. ex: \( \zeta \) Puppis (Kahn et al. 2001), Cassinelli et al. 2001. Rate of photo-excitation (in \( \text{s}^{-1} \)) (Mewe & Schrijver 1978) in a stellar photospheric radiation field with effective black-body radiation temperature \( T_{rad} \) is written as:

\[
B_{mpk} = \frac{W A_{mpk} (w_{pk} / w_m)}{\exp\left(\frac{\Delta E_{mpk}}{kT_{rad}}\right)} - 1, \tag{7}
\]

where \( A \) and \( B \) are the Einstein coefficients and the radiation is diluted by a factor \( W \) given by

\[
W = \frac{1}{2} \left[ 1 - \left(1 - \frac{T_{rad} \gamma}{T_e}\right)^{1/2} \right]. \tag{8}
\]

- \( W=1/2 \) (close to the stellar surface, \( r = r_s \); e.g., Capella and Procyon: Audard et al. 2002, Mewe et al. 2001, Ness et al. 2001).
- \( W< 1/2 \) (radiation originates from another star at larger distance; e.g., Algol, where K-star is irradiated by B-star, \( W \simeq 0.01 \); Ness et al. 2002).

Porquet et al. (2001) showed that photo-excitation is important for \( \text{C}^5 \), \( \text{N}^6 \), \( \text{O}^7 \) for \( T_{rad} \gtrsim 5 \) \( 10^3 \) K (see Fig. 3), and for higher-Z ions when \( T_{rad} \gtrsim 10^4 \) K.

#### 5.2. Influence on Ionization Process Diagnostic

Recently, Kinkhabwala et al. (2002), pointed out the important effect of the photo-excitation in the high Rydberg series lines. Indeed, the ratio of high-\( n \) lines to Ly\( \alpha \) bring evidence for photo-excitation in Warm Absorber Seyfert 2. They clearly showed that in addition to photo-ionization (treated in Porquet & Dubau 2000), photo-excitation process is sufficient to fit the data of Seyfert galaxies without needing an additional collisional ionization process (e.g. shock or starburst). Then both photo-ionization and photo-excitation are needed to inferred unambiguously the ionization process occurring in the plasmas.
6. Conclusion

Helium-like density and temperature diagnostics has now become a powerful tool in the analysis of the high resolution Chandra and XMM-Newton X-ray spectra (Porquet & Dubau 2000). Therefore, we have revisited the calculations of the ratios $R = z/(x+y)$ and $G = ((x+y)+z)/w$ of the $z$, $(x+y)$, and $w$ “triplet” lines of the He-like ions CV, NVI, Ovii, Neix, Mgxi, SiXIII, taking into account all relevant processes and improved atomic data. The calculations were done for optically thin plasmas in collisional ionization equilibrium (e.g., stellar coronae: Porquet, Mewe et al. 2001). The influence of an external radiation field on the depopulation of the upper level of $z$ is considered which can be important for hot OB or F stars (e.g., ζ Puppis, Procyon, and Algol). In preparation are improved calculations for photo-ionized and hybrid plasmas (e.g., warm absorber in AGNs: Porquet, Kaasstra, Mewe, Dubau 2002), and will be extended to transient ionization plasmas (young SNRs: Kaasstra, Mewe, Porquet, Raassen 2002), where inner-shell ionization of the Li-like ion can contribute significantly to the intensity of the forbidden line (see also Mewe [2002]).

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