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# Line ratios for Helium-like ions: Applications to collision-dominated plasmas

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**Abstract.** The line ratios  $R$  and  $G$  of the three main lines of He-like ions (triplet: *resonance*, *intercombination*, *forbidden* lines) are calculated for C V, N VI, O VII, Ne IX, Mg XI, and Si XIII. These ratios can be used to derive electron density  $n_e$  and temperature  $T_e$  of hot late-type stellar coronae and O, B stars from high-resolution spectra obtained with *Chandra* (*LETGS*, *HETGS*) and *XMM-Newton* (*RGS*). All excitation and radiative processes between the levels and the effect of upper-level cascades from collisional electronic excitation and from dielectronic and radiative recombination have been considered. When possible the best experimental values for radiative transition probabilities are used. For the higher- $Z$  ions (i.e. Ne IX, Mg XI, Si XIII) possible contributions from blended dielectronic satellite lines to each line of the triplets were included in the calculations of the line ratios  $R$  and  $G$  for four specific spectral resolutions: *RGS*, *LETGS*, *HETGS-MEG*, *HETGS-HEG*. The influence of an external stellar radiation field on the coupling of the  $2^3S$  (upper level of the *forbidden* line) and  $2^3P$  levels (upper levels of the *intercombination* lines) is taken into account. This process is mainly important for the lower- $Z$  ions (i.e. C V, N VI, O VII) at moderate radiation temperature ( $T_{\text{rad}}$ ). These improved calculations were done for plasmas in collisional ionization equilibrium, but will be later extended to photo-ionized plasmas and to transient ionization plasmas. The values for  $R$  and  $G$  are given in extensive tables\*, for a large range of parameters, which could be used directly to compare to the observations.

**Key words.** X-rays: stars: – atomic processes – stars: coronae – stars: late-type – stars: activity – early-type stars: activity

\* Tables 4 to 69 and A.1 to A.6 are only available in electronic form at the CDS via anonymous ftp to cdsarc.u-strasbg.fr (130.79.128.5) or via <http://cdsweb.u-strasbg.fr/cgi-bin/qcat?J/A+A/>.

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## 1. Introduction

The new generation of X-ray satellites (*Chandra*, *XMM-Newton*) enables us to obtain unprecedented high spectral resolution and high S/N spectra. The wavelength ranges of the *RGS*<sup>1</sup> (6–35 Å), of the *LETGS*<sup>2</sup> (2–175 Å), and of the *HETGS*<sup>3</sup> (MEG range: 2.5–31 Å; HEG range: 1.2–15 Å) contain the Helium-like line “triplets” from C V (or N VI for the *RGS*, and for the *HETGS-HEG*) to Si XIII. The triplet consists of three close lines: the *resonance* line, the *intercombination* line and the *forbidden* line. The Helium-like triplets provide electron density ( $n_e \sim 10^8\text{--}10^{13} \text{ cm}^{-3}$ ) as well as electron temperature ( $T \sim 1\text{--}10 \text{ MK}$ ) as first shown by Gabriel & Jordan (1969). The line ratios of these He-like triplets enable also the determination of the ionization processes (photo-ionization and/or collisional ionization) which prevail in the plasma (Porquet & Dubau 2000, Liedahl 1999).

The ratios of these lines are already widely used for collisional solar plasma diagnostics (e.g., Gabriel & Jordan 1969, Doyle 1980, Keenan et al. 1987, McKenzie & Landecker 1982).

Recently, also theoretical calculations for photo-ionized plasmas or “hybrid” plasmas (photo-ionization plus collisional ionization) have been given by Porquet & Dubau (2000) (hereafter referred to as **Paper I**). Their calculations have been already applied to spectra of Seyfert galaxies (e.g. NGC 5548, Kaastra et al. 2000; Mkn 3, Sako et al. 2000; NGC 4151, Ogle et al. 2000; NGC 4051, Collinge et al. 2001, etc...).

We present here calculations of these ratios, from C V to Si XIII, which could be applied directly for the first time to *Chandra* and *XMM-Newton* observations of extra-solar collisional plasmas such as stellar coronae. These calculations have been done to apply an improved model to the density analysis of the *RGS*, the *LETGS* and the *HETGS* spectra of various late-type stars such as Capella, Procyon, and  $\alpha$  Centauri (e.g., Audard et al. 2001, Ness et al. 2001a, Mewe et al. 2001) and also to O stars such as  $\zeta$  Puppis (Kahn et al. 2001). Our model is to be considered as an improvement of various previous calculations for solar plasmas such as done by e.g., Gabriel & Jordan (1969), Blumenthal et al. (1972), Mewe (1972), Mewe & Schrijver (1978a, 1978b, 1978c), Pradhan & Shull (1981), Mewe & Gronenschild (1981), Mewe et al. (1985), and Pradhan (1982, 1985). The calculations are partly based on recent work by Porquet & Dubau (2000).

In the next three sections, we introduce the plasma diagnostics and the atomic processes and atomic data taken into account in the calculations. In sect. 5, we display the results for  $R$  and  $G$  calculated for four specific spectral resolutions (Full Width at Half Maximum: FWHM):

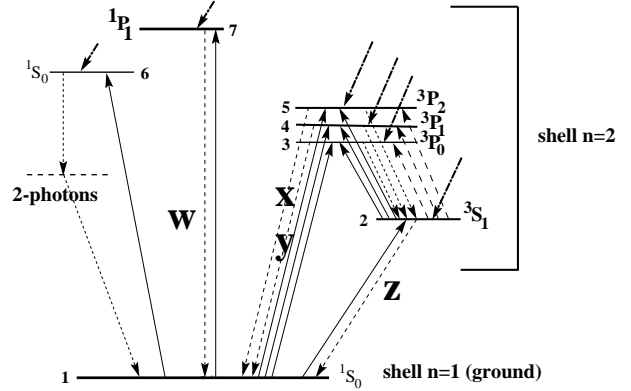
<sup>1</sup> *RGS*: Reflection Grating Spectrometer on board *XMM-Newton* (den Herder et al. 2001).

<sup>2</sup> *LETGS*: Low Energy Transmission Grating Spectrometer on board *Chandra* (Brinkman et al. 2000).

<sup>3</sup> *HETGS*: High Energy Transmission Grating Spectrometer on board *Chandra* (Canizares et al. 2000).

*RGS*, *LETGS*, *HETGS-MEG*, *HETGS-HEG*, over a broad range of physical parameters:  $n_e$ ,  $T_e$ , radiation temperature ( $T_{\text{rad}}$ ), and radiation dilution factor ( $W$ ).

## 2. Plasma diagnostics



**Fig. 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  $2^3S_1$  to  $2^3P_{0,1,2}$  levels, and 2-photon continuum from  $2^1S_0$  to the ground level), and *thick skew arrows*: recombination (radiative and dielectronic) plus cascade processes.

In the X-ray range, the three most intense lines of Helium-like ions (“triplet”) are: the *resonance* line ( $w$ , also called  $r$ :  $1s^2^1S_0 - 1s2p^1P_1$ ), the *intercombination* lines ( $x + y$ , also called  $i$ :  $1s^2^1S_0 - 1s2p^3P_{2,1}$ ) and the *forbidden* line ( $z$ , also called  $f$ :  $1s^2^1S_0 - 1s2s^3S_1$ ). They correspond to transitions between the  $n=2$  shell and the  $n=1$  ground-state shell (see Figure 1). The wavelengths in Å of each line from C V ( $Z=6$ ) to Si XIII ( $Z=14$ ) are reported in Table 1.

**Table 1.** Wavelengths in Å of the three main X-ray lines of C V, N VI, O VII, Ne IX, Mg XI and Si XIII (from Vainshtein & Safronova 1978).

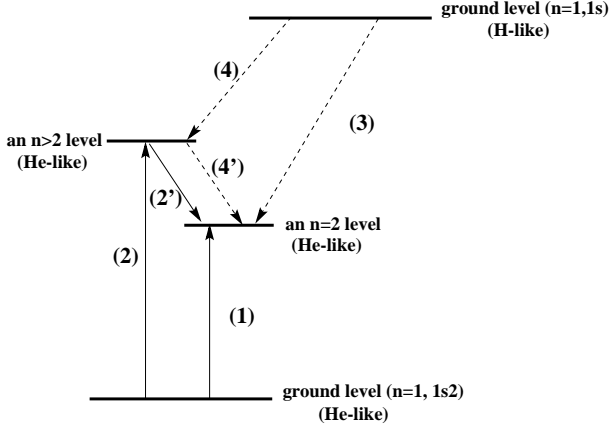
line	label	C V	N VI	O VII	Ne IX	Mg XI	Si XIII
<i>resonance</i>	$w$ ( $r$ )	40.279	28.792	21.603	13.447	9.1681	6.6471
<i>inter-</i>	$x$	40.711	29.074	21.796	13.548	9.2267	6.6838
<i>combination</i>	$y$	40.714	29.076	21.799	13.551	9.2298	6.6869
<i>forbidden</i>	$z$ ( $f$ )	41.464	29.531	22.095	13.697	9.3134	6.7394

As shown by Gabriel & Jordan (1969), the ratios defined below are sensitive to the electron density and to the electron temperature:

$$R(n_e) = \frac{z}{x+y} \quad \left( \text{also } \frac{f}{i} \right) \quad (1)$$

$$G(T_e) = \frac{z + (x + y)}{w} \quad \left( \text{also } \frac{f + i}{r} \right) \quad (2)$$

### 2.1. Density diagnostic



**Fig. 2.** Simplified diagram showing the different contributions to the population of a given  $n=2$  shell level. (1): direct contribution due to collisional excitation from the ground level ( $1s^2$ ) of He-like ions; (2)+(2'): collisional excitation plus upper-level radiative cascade contribution; (3): direct radiative recombination or direct dielectronic recombination from H-like ions; and (4)+(4'): radiative recombination or dielectronic recombination plus upper-level radiative cascade contribution.

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 Figure 2). These states decay radiatively directly or by cascades to the ground level. The relative intensities of the three intense lines are then independent of density. As  $n_e$  increases from the low-density limit, some of these states ( $1s2s\ ^3S_1$  and  $1S_0$ ) are depleted by collisions to the nearby states where  $n_{\text{crit}} C \sim A$ , with  $C$  being the collisional coefficient rate,  $A$  being the radiative transition probability from  $n=2$  to  $n=1$  (ground state), and  $n_{\text{crit}}$  being the critical density. Collisional excitation depopulates first the  $1s2s\ ^3S_1$  level (upper level of the *forbidden* line) to the  $1s2p\ ^3P_{0,1,2}$  levels (upper levels of the *intercombination* lines). The intensity of the *forbidden* line decreases while those of the *intercombination* lines increase, hence implying a reduction of the ratio  $R$  (according to Eq. 1), over approximately two or three decades of density (see Fig. 8 in Paper I). For much higher densities,  $1s2s\ ^1S_0$  is also depopulated to  $1s2p\ ^1P_1$ , and the *resonance* line becomes sensitive to the density (this has been nicely illustrated by Gabriel & Jordan (1972) in their Fig. 4-6-9). However caution should be taken for low- $Z$  ions (i.e. C V, N VI, O VII) since in case of an intense UV radiation field, the photo-excitation between the  $^3S$  term and the  $^3P$  term is not negligible. This process has the same effect on the

*forbidden* line and on the *intercombination* line as the collisional coupling, i.e. lowering of the ratio  $R$ , and thus could mimic a high-density plasma. It should be taken into account to avoid any misunderstanding between a high-density plasma and a high radiation field (see §4.4 for more details).

### 2.2. Temperature and ionization process diagnostics

The ratio  $G$  (see Eq. 2) 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 Paper I (see also Mewe 1999, and Liedahl 1999), the relative intensity of the *resonance*  $w$  (or  $r$ ) line, compared to the *forbidden*  $z$  (or  $f$ ) and the *intercombination*  $x + y$  (or  $i$ ) 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  $G = (z + (x + y))/w \sim 1$  (or  $(f + i)/r \sim 1$ ). On the contrary, a weak *resonance* line corresponds to plasmas dominated by the photo-ionization ( $G = (z + (x + y))/w > 4$ , or  $(f + i)/r > 4$ ).

## 3. Schematic model

We illustrate the relevant processes in the formation of the *resonance*, *intercombination*, and *forbidden* lines with a simplified level scheme (cf. Mewe & Schrijver 1978a) consisting of the following levels denoted by short labels:  $g$ : ground level  $1^1S_0$ ;  $m'$ : upper metastable level  $2^1S_0$  of the two-photon transition;  $1'$ : upper level  $2^1P_1$  of the *resonance* line;  $m$ : upper metastable level  $2^3S_1$  of the *forbidden* ( $f$ ) line;  $p_k$  ( $k = 1, 2, 3$ : levels  $2^3P_k$  ( $2^3P_1$  is the upper level of the by far the strongest component ( $y$ ) of the *intercombination* line  $i$ , and  $2^3P_2$  is the upper level of the weaker component ( $x$ ));  $c$ : continuum level which lumps together all higher levels to represent the cascades from excitation and recombination processes.

The electron collisional rate coefficient (in  $\text{cm}^3 \text{s}^{-1}$ ) for transition  $j \rightarrow k$  is written as:

$$C_{jk} = 8.63 \cdot 10^{-6} \frac{\gamma_{jk}}{w_j \sqrt{T_e}} \exp\left(-\frac{\Delta E_{jk}}{kT_e}\right), \quad (3)$$

where  $\Delta E_{jk}$  is the excitation energy,  $T_e$  is the electron temperature in K,  $\gamma_{jk}$  the collision strength averaged over a Maxwellian electron energy distribution, and  $w_j$  the statistical weight of the initial level  $j$ .

The total rate coefficients for the formation of the *forbidden* ( $f$  or  $z$  notation) and *intercombination* ( $i$  or  $x + y$ ) line can be written as (e.g., Mewe & Schrijver 1978a, Eqs. 18–30):

$$I_f = BR_{mg} \left[ C_{gm} + \sum_{k=0}^2 BR_{pkm} C_{gp_k} \right], \quad (4)$$

$$I_i = \sum_{k=1}^2 BR_{p_k g} \left[ C_{gp_k} + BR_{mp_k} C_{gm} \right], \quad (5)$$

with the various branching ratios:

$$BR_{mg} = \frac{A_{mg}}{A_{mg} + n_e S'_{mp}}, \quad (6)$$

$$S'_{mp} = \sum_{k=1}^2 C_{mp_k} BR'_{p_k g}, \quad (7)$$

$$BR_{p_k m} = \frac{A_{p_k m}}{A_{p_k m} + A_{p_k g}} \quad (BR_{p_0 m} \equiv 1), \quad (8)$$

$$BR'_{p_k g} = \frac{A_{p_k g}}{A_{p_k g} + A_{p_k m}} \quad (BR'_{p_0 g} \equiv 0), \quad (9)$$

$$BR_{p_k g} = \frac{A_{p_k g}}{A_{p_k g} + A_{p_k m} BR_{mg}} \quad (BR_{p_0 g} \equiv 0), \quad (10)$$

$$BR_{mg} = \frac{A_{mg}}{A_{mg} + n_e S_{mp}}, \quad (11)$$

$$BR_{mp_k} = \frac{n_e C_{mp_k}}{A_{mg} + n_e S_{mp}}, \quad (12)$$

$$S_{mp} = \sum_{k=0}^2 C_{mp_k}. \quad (13)$$

Analogously we can derive the total rate coefficients for the formation of the *resonance* (*r* or *w*) line or two-photon radiation (2ph) by substituting  $m \rightarrow m'$ ,  $p, p_k \rightarrow 1'$  and performing no summation:

$$I_r = BR_{1'g} \left[ C_{g1'} + BR_{m'1'} C_{gm'} \right], \quad (14)$$

$$I_{2ph} = BR_{m'g} \left[ C_{gm'} + BR_{1'm} C_{g1'} \right], \quad (15)$$

and changing all  $BR$ 's etc. appropriately.

We note that the collision coefficients  $C_{jk}$  include also the  $n > 2$  cascades. The radiative transition probabilities are tabulated in the Table 2 of Paper I and the effective collision strengths  $\gamma$  in their Tables 9–13 and in their Fig. 4. We assume in this section that the electron density is so low that the collision de-excitation rate  $n_e C_{p_k m}$  can be neglected with respect to the spontaneous radiative rate  $A_{p_k m}$  (e.g., for C V  $n_e C_{p_k m} < A_{p_k m}$  for  $n_e < 10^{15} \text{ cm}^{-3}$ ). This can be easily taken into account by the substitution

$$A_{p_k m} \rightarrow A_{p_k m} + n_e C_{p_k m}. \quad (16)$$

Further, all collision processes that couple the singlet and triplet system are neglected in this schematic model. It turns out that at high density the coupling  $m, p_k \leftrightarrow m', 1'$  cannot be neglected.

In the full calculations used in this work (see §5), the coupling between the singlet and triplet system has been

taken into account, as well as the collisional de-excitation.

If we take also into account the contribution from radiative and dielectronic recombinations of the Hydrogen-like ion we substitute

$$C_{gk} \rightarrow C_{gk} + \alpha'_{ck}, \quad (17)$$

where  $k = m$  or  $k = p_k$ , respectively, and

$$\alpha'_{ck} = (N_H/N_{He}) \alpha_{ck}, \quad (18)$$

where  $\alpha_{ck}$  is the total radiative and dielectronic recombination rate coefficient including cascades and  $N_H/N_{He}$  is the abundance ratio of Hydrogen-like to Helium-like ions (e.g. taken from Arnaud & Rothenflug 1985, Mazzotta et al. 1998). The recombination coefficients are given in Tables 3–8 in Paper I. However, for a collision-dominated plasma, the recombination generally gives only a minor effect (i.e. far less than few percents), but are nevertheless introduced in the full calculations in section 5.

Mewe & Schrijver (1978a) took also into account the effect of a stellar radiation field (also called photo-excitation) with effective radiation temperature  $T_{\text{rad}}$ . This can be done by substituting in the above equations:

$$n_e C_{mp_k} \rightarrow n_e C_{mp_k} + B_{mp_k}, \quad (19)$$

$$n_e S_{mp} \rightarrow n_e S_{mp} + B_{mp}, \quad (20)$$

where  $B_{mp} = \sum_{k=0}^2 B_{mp_k}$  and

$$B_{mp_k} = \frac{W A_{p_k m} (w_{p_k}/w_m)}{\exp\left(\frac{\Delta E_{mp_k}}{kT_{\text{rad}}}\right) - 1}, \quad (21)$$

is the rate (in  $\text{s}^{-1}$ ) of absorption  $m \rightarrow p_k$  and  $W$  is the dilution factor of the radiation field (as a special case we take  $W = \frac{1}{2}$  close to the stellar surface). We have checked that the radiation field is so low that the induced emission rate  $B_{p_k m} = (w_m/w_{p_k}) B_{mp_k}$  is negligible respect to the spontaneous radiative rate  $A_{p_k m}$ . Nevertheless, in the full calculations used in this work (see §5), we have taken into account induced emission as well as photo-excitation.

Mewe & Schrijver (1978a) considered also inner-shell ionization of the Lithium-like ion which can give an important contribution to the *forbidden* line in a transient plasma (Mewe & Schrijver 1978b) such as a supernova remnant. However, in the present calculations we neglect this because we consider plasmas in ionization equilibrium.

Finally, Mewe & Schrijver (1978a, 1978c) have considered also excitation  $2^3\text{S} \rightarrow 2^3\text{P}$  by proton collisions using approximations of Coulomb-Born results from Blaha (1971). In a new version (SPEX90) of our spectral code SPEX (Kaastra et al. 1996), which contains for the H- and He-like ions an improvement of the known MEKAL code (Mewe et al. 1985, 1995a), proton collisions are taken into account based on Blaha's results. Test calculations with SPEX90 show that for an equilibrium plasma in all

practical cases proton excitation is negligible compared to electron excitation.

In the case where  $N_H/N_{He} \gg 1$ , recombination is dominant e.g., for photo-ionized plasmas it turns out that the ratios  $R \equiv f/i$  are for collisional and photo-ionized plasmas comparable in the same density range (cf. also Mewe 1999), but the ratios  $G \equiv (i + f)/r$  are very different, e.g.,  $G \sim 1$  for a collisional plasma and a factor  $\sim 2$ -4 larger for a photo-ionized plasma where the *resonance* line is relatively much weaker.

#### 4. Atomic data and improvements

The intensities of the three lines (*resonance*, *forbidden* and *intercombination*) are calculated mainly from atomic data presented in Paper I (Porquet & Dubau 2000). In this work (as well as in Paper I) for all temperatures (low and high), radiative recombination contributions (direct + upper-level radiative cascades), and collisional excitations inside the  $n=2$  shell were included in the line ratio calculations. For high temperatures, the collisional excitation contribution (direct + near-threshold resonance + cascades) from the ground level ( $n=1$  shell,  $1s^2$ ) are important as well as dielectronic recombination (direct + cascades).

Excitation collisional data are also taken from Paper I, which are based on the calculations from Zhang & Sampson (1987) plus the contribution of the upper-level ( $n > 2$ ) radiative cascades calculated in Paper I (see Paper I for more details).

The ionization balance is from Mazzotta et al. (1998) and the data for radiative and dielectronic recombinations are from Paper I. Various new data for the transition probabilities (e.g., *forbidden* and *intercombination* lines) have been selected (see § 4.1).

In the following paragraphs we describe the several differences between Paper I and this work:  $A_{ki}$ , optical depth, contribution of the blended dielectronic satellite lines, and radiation field.

##### 4.1. Update of the $A_{ki}$ for the forbidden and the intercombination lines

We have updated the transition probabilities  $A_{ki}$  reported in Paper I for the *intercombination* ( $y, A_{1 \rightarrow 4}$ ) and the *forbidden* ( $z, A_{1 \rightarrow 2}$ ) line by published experimental values (see Table 2, and references therein). In some cases, no published experimental values has been found and then we used the theoretical values from Lin et al. (1977). Indeed, comparisons of their theoretical values with the experimental values reported in Table 2 seem to show good agreement in other cases.

For C V, the ratio  $R$  is reduced by about 20% comparing the calculations using the values of  $A_{ki}$  reported in Paper I, while for N VI the reduction is less than 10%. For

**Table 2.** Update of the transition probabilities ( $s^{-1}$ ) with published experimental values for the *forbidden* line ( $z, A_{1 \rightarrow 2}$ ) and the *intercombination* line ( $y, A_{1 \rightarrow 4}$ ) compared to the theoretical values from Porquet & Dubau (2000).

ion	<i>forbidden</i> line ( $z, A_{1 \rightarrow 2}$ )	<i>intercombination</i> line ( $y, A_{1 \rightarrow 4}$ )
C V	4.857 (+1) (S94)	2.90 (+7) (H85)
N VI	2.538 (+2) (N00)	1.38 (+8) (H85)
O VII	1.046 (+3) (C98)	5.800 (+8) (E81)
Ne IX	1.09 (+4) (T99)	5.400 (+9) *
Mg XI	7.347 (+4) (S95)	3.448 (+10) (A81)
Si XIII	3.610 (+5) *	1.497 (+11) (A79)

(A79) : Armour et al. (1979)

(A81) : Armour et al. (1981)

(C98) : Crespo López-Urrutia et al. (1998)

(E81) : Engström et al. (1981)

(H85) : Hutton et al. (1985)

(N00) : Neill et al. (2000)

(S94) : Schmidt et al. (1994)

(S95) : Stefanelli et al. (1995)

(T99) : Träbert et al. (1999)

\* : Theoretical values taken from Lin et al. (1977), see text (§4.1).

O VII, Ne IX, Mg XI, and Si XIII, the differences between the current calculations using these new values of  $A_{ki}$  and those reported in Paper I are negligible.

##### 4.2. Influence of the optical depth (resonant scattering)

Schrijver et al. (1995) and Mewe et al. (1995b) have investigated the possibility that resonance photons are scattered out of the line of sight in late-type stellar coronae (see also Acton 1978). Indeed, in this process, a *resonance* line photon is absorbed by an ion in the ground state and then re-emitted, generally in a different direction. So, the total photon intensity integrated over  $4\pi$  remains unchanged but the photon distribution with respect to given direction is altered. This absorption and re-emission is indistinguishable from scattering and depends on the geometry of the region being observed. In general, photons would be scattered preferentially out of the line of sight for active regions (relatively dense areas) and into the line of sight for the surrounding quiet Sun (less dense area), see Schmelz et al. (1997) and Mewe et al. (2001). The effect is smaller for instruments with a larger field of view.

This could have an impact on the temperature diagnostic, the so-called  $G = (z + x + y)/w$  or  $(f + i)/r$  ratio. If the optical depth of the line is not taken into account, the calculated intensity ratio  $G$  can be overestimated and the inferred temperature from the  $G$  ratio is underestimated.

As detailed in Mewe et al. (2001), branching ratios can be used to check the assumption of the optical thin model because effects of resonance scattering would affect the measured branching ratio. From the fact that the intensities of e.g., the strong resonance lines Fe XVIII  $\lambda 93.92$  and Fe XIX  $\lambda 108.307$  are in good agreement with the intensities of other lines sharing the same upper level, one can de-

rive a constraint on the optical depth taking into account the systematic uncertainties of the theoretical transition probabilities  $A$  (typical 25% for each  $A$ , hence 35% for the branching ratio) which dominate over the statistical errors (typically 10%). If we rule out a reduction in the resonance line intensity larger than about 30%, then on the basis of a simple “escape-factor” model with

$$P(\tau) \simeq \frac{1}{[1 + 0.43\tau]}, \quad (22)$$

the escape factor for a homogeneous mixture of emitters and absorbers in a slab geometry (e.g., Kaastra & Mewe 1995), one can put a constraint on the optical depth. The optical depth  $\tau$  for a Doppler-broadened resonance line can be written as (Mewe et al. 1995b)<sup>4</sup>:

$$\begin{aligned} \tau &= 1.16 \cdot 10^{-17} \left( \frac{n_i}{n_{el}} \right) A_Z \left( \frac{N_H}{n_e} \right) \lambda f \sqrt{\frac{M}{T_e}} n_e l \\ &\equiv 10^{-19} C_d \left( \frac{A_Z}{A_{Z\odot}} \right) \left( \frac{n_e l}{\sqrt{T_6}} \right), \end{aligned} \quad (23)$$

where  $(n_i/n_{el})$  is the ion fraction (e.g. from Arnaud & Rothenflug 1985, from Arnaud & Raymond 1992 for iron, or from Mazzotta et al. 1998),  $A_Z$  is the elemental abundance relative to hydrogen,  $A_{Z\odot}$  the corresponding value for the solar photosphere as given by Anders & Grevesse (1989),  $N_H/n_e \simeq 0.85$  the ratio of hydrogen to electron density,  $\lambda$  is the wavelength in Å,  $f$  the absorption oscillator strength,  $M$  is the atomic weight,  $T_e$  is the electron temperature (in K or  $T_6$  in MK),  $l$  a characteristic plasma dimension (in cm) and

$$C_d \equiv 98.5 \left( \frac{n_i}{n_{el}} \right) A_{Z\odot} \lambda f \sqrt{M}. \quad (24)$$

According to Equation (23), Ness et al. (2001a) estimated the optical depth, adopting a value of unity for the fractional ionization and using solar abundances. One further assumes  $T_e$  at the peak line formation, but note that  $\tau$  is rather insensitive to the precise value of  $T_e$ . One can determine – for each *resonance* line – that value of  $n_e l$  which yields an optical depth of unity. According to the values of  $n_e$  inferred from the ratio  $R = z/(x + y)$  or  $R = f/i$  (from C V to Si XIII the *intercombination* and the *forbidden* lines are not sensitive to resonant scattering below a column density of  $\mathcal{N}_H \sim 10^{25-26} \text{ cm}^{-2}$  and  $\mathcal{N}_H \sim 10^{30-31} \text{ cm}^{-2}$ , respectively, while the resonance line becomes sensitive to the resonant scattering above  $\mathcal{N}_H \sim 10^{21-23} \text{ cm}^{-2}$ ), one can determine the corresponding values of  $l$ . One can compute the respective emission measures of  $n_e^2 \ell^3$  respectively, and can compare these emission measures with those derived from the measured line fluxes  $f_\lambda$  according to

$$EM = \frac{4\pi d^2 f_\lambda}{P_\lambda(T_e)} \quad (25)$$

<sup>4</sup> the forefactor in the first part of Eq. (23) was in Mewe et al. (1995b,2001) erroneously taken a factor of  $10^3$  too large, but the 2nd part of Eq. (23) is still correct.

with the line emissivity  $P_\lambda(T_e)$  and the distance  $d$  of the star. If the former is larger, this inconsistency shows that the assumption of a non-negligible optical depth is invalid and we conclude that optical depth effects are irrelevant for the analysis of He-like triplets. On the contrary the effect of resonant scattering should be taken into account when comparing the theoretical values with the observational ones.

Since  $\tau_r \gg \tau_i$  ( $\tau_r$  and  $\tau_i$  corresponding respectively to the optical depth of the *resonance* and the *intercombination* lines), we can write  $G_\tau \equiv \frac{G}{P_r}$ , where  $G_\tau$  is the value of the ratio taken into account the optical depth of the *resonance* line,  $G$  is the value without resonant scattering (such as in Paper I and §5), and  $P_r$  is the escape probability for the *resonance* line (Eq. 22). One should note that  $G_\tau$  is not strictly exact when the contribution of the blended dielectronic satellite lines are introduced in the calculations (see §4.3).

### 4.3. Blended dielectronic satellite lines

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:

$$I_s = N_{\text{He}} n_e C_s, \quad (26)$$

where  $N_{\text{He}}$  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):

$$C_s = 2.0706 \cdot 10^{-16} \frac{e^{-E_s/kT_e}}{g_1 T_e^{3/2}} F_2(s), \quad (27)$$

where  $E_s$  is the energy of the satellite level  $s$  with statistical weight  $g_s$  above the ground state 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

$$F_2(s) = \frac{g_s A_a A_r}{(A_a + \sum A_r)}, \quad (28)$$

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

For a group of satellites with the same principal quantum number  $n$ ,  $E_s$  can be approximated by

$$E_s [\text{eV}] = 1.239842 \cdot 10^4 \frac{a_{DR}}{\lambda}, \quad (29)$$

where  $\lambda$  is the wavelength (Å) of the satellite line and  $a_{DR} \simeq 0.7, 0.86, 0.92,$  and  $0.96$  for  $n = 2, 3, 4,$  and  $> 4$ ,

respectively (Mewe & Gronenschild 1981). For  $\lambda$  in Å and  $T$  in K we can write:

$$\frac{E_s}{kT} = \frac{a_{DR}hc}{\lambda kT} = 1.439 \cdot 10^8 \frac{a_{DR}}{\lambda T}. \quad (30)$$

The influence of the blending of dielectronic satellite lines for the *resonance*, the *intercombination* and the *forbidden* lines has been taken into account where 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, i.e. Ne IX, Mg XI, and Si XIII ( $Z=10, 12$ , and  $14$ , respectively). 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 (i.e.  $\Delta\lambda=0.073, 0.075$  and  $0.078\text{Å}$  for Ne IX, Mg XI and Si XIII respectively), LETGS (i.e.  $\Delta\lambda=0.05\text{Å}$ ), HETGS-MEG (i.e.  $\Delta\lambda=0.023\text{Å}$ ), and HETGS-HEG (i.e.  $\Delta\lambda=0.012\text{Å}$ ).

For the  $n=2, 3, 4$  blended dielectronic satellite lines we use the atomic data reported in the appendix. For the higher- $n$  blended dielectronic satellite lines we use the results from Karim and co-workers. For  $Z=10$  (Ne IX) we use the data from Karim (1993) who gives the intensity factor  $F_2^* \equiv F_2/g_1$  for the strongest ( $F_2^* > 10^{12} \text{s}^{-1}$ ) dielectronic satellite lines with  $n=5-8$ . For  $Z=14$  (Si XIII), we take the calculations from Karim & Bhalla (1992) who report the intensity factor  $F_2^*$  for the strongest ( $F_2^* > 10^{12} \text{s}^{-1}$ ) dielectronic satellite lines with  $n=5-8$ . For  $Z=12$  (Mg XI) we have interpolated between the calculations from Karim (1993) for  $Z=10$ , and from Karim & Bhalla (1992) for  $Z=14$ .

Including the contribution of the blended dielectronic satellite lines, we write for the ratios  $R$  and  $G$ :

$$R = \frac{z + satz}{(x + y) + satxy} \quad (31)$$

$$G = \frac{(z + satz) + ((x + y) + satxy)}{(w + satw)}, \quad (32)$$

where  $satx$ ,  $satxy$  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  $^3\text{P}$  levels are depleted to the  $^1\text{P}$  level, and in that case  $x+y$  decreases and  $R$  tends to  $satz/satxy$ .

At the temperature at which the ion fraction is maximum for the He-like ion (see e.g. Arnaud & Rothenflug 1985, 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 Ne IX, Mg XI, and Si XIII at the low-density limit and for  $T_{rad}=0\text{K}$ , respectively. On the other hand, for much lower electron temperatures, the effect is bigger since the intensity of the dielectronic satellite lines is proportional to  $T_e^{-3/2}$ . As well, for high values of density ( $n_e$ ) at which the intensity

of the *forbidden* line is very weak (i.e. tends to zero), the contribution of the blended dielectronic satellite lines to the *forbidden* line leads to a ratio  $R$  which decreases much slower with  $n_e$  than in the case where the contribution of the blended dielectronic satellite lines is not taken into account.

#### 4.4. Influence of a radiation field

Recently, Kahn et al. (2001) have found with the RGS on XMM-Newton that for  $\zeta$  Puppis, the *forbidden* to *intercombination* line ratios within the Helium-like triplets are abnormally low for N VI, O VII, and Ne IX. While this is sometimes indicative of a high electron density, they have shown that in the case of  $\zeta$  Puppis, it is instead caused by the intense radiation field of this star. This constrains the location of the X-ray emitting shocks relative to the star, since the emitting regions should be close enough to the star in order that the UV radiation is not too much diluted.

A strong radiation field can mimic a high density if the upper ( $^3\text{S}$ ) level of the *forbidden* line is significantly depopulated via photo-excitation to the upper ( $^3\text{P}$ ) levels of the *intercombination* lines, analogously to the effect of electronic collisional excitation (fig. 1). The result is an increase of the *intercombination* lines and a decrease of the *forbidden* line.

Eq. (21) gives the expression for photo-excitation from level  $m$  to level  $p_k$  in a radiation field with effective black-body temperature  $T_{rad}$  from a hot star underlying the X-ray line emitting plasma. As pointed out by Mewe & Schrijver (1978a) the radiation is diluted by a factor  $W$  given by

$$W = \frac{1}{2} \left[ 1 - \left( 1 - \left( \frac{r_*}{r} \right) \right)^{1/2} \right], \quad (33)$$

where  $r$  is the distance from the center of the stellar source of radius  $r_*$ . Close to the stellar surface the dilution factor  $W = \frac{1}{2}$ . For stars such as Capella or Procyon, we can take  $W = \frac{1}{2}$ , because the stellar surface which is the origin of the radiation irradiates coronal structures that are close to the stellar surface (Ness et al. 2001a). In a star such as Algol the radiation originates from another star, and  $W$  is much lower (i.e.  $W \simeq 0.01$ , cf. Ness et al. 2001b), but due to the strong radiation field the radiation effect can still be important.

In their Table 8, Mewe & Schrijver (1978a) give for information the radiation temperature for a solar photospheric field for  $Z=6, 7$ , and  $8$ . In Table 3, we report the wavelengths at which the radiation temperature should be estimated for  $Z=6, 7, 8, 10, 12, 14$ . These wavelengths correspond to the transitions between the  $^3\text{S}$  and  $^3\text{P}$  levels ( $\lambda_{f \rightarrow i}$ ) and the  $^1\text{S}$  and  $^1\text{P}$  levels ( $\lambda_{6 \rightarrow r}$ ).

The photo-excitation from the  $^3\text{S}$  level and  $^3\text{P}$  levels is very important for low- $Z$  ions C V, N VI, O VII. For higher- $Z$  ions, this process is only important for very high

**Table 3.** Wavelengths at which the radiation temperature ( $T_{rad}$ ) should be determined.

	C V	N VI	O VII	Ne IX	Mg XI	Si XIII
$\lambda_{f \rightarrow i}$ (Å)	2280	1906	1637	1270	1033	864
$\lambda_{6 \rightarrow r}$ (Å)	3542	2904	2454	1860	1475	1200

radiation temperature (  $\sim$ few 10 000 K).

One can note that the photo-excitation between the levels  $^1S_0$  and  $^1P_1$  is negligible compared to the photo-excitation between the  $^3S_1$  and  $^3P_{0,1,2}$  levels. For example, for a very high value of  $T_{rad}=30\,000$  K the difference between the calculations taken or not taken into account the photo-excitation between  $^1S_0$  and  $^1P_1$  is smaller than 20% for C V, where this effect is expected to be maximum.

## 5. Results from extended calculations

Using the above-mentioned atomic data, we have calculated the line intensity ratios  $R$  and  $G$  for C V, N VI, O VII, Ne IX, Mg XI, and Si XIII<sup>5</sup> The wavelengths of these three (four) lines for each He-like ion treated in this paper are reported in Table 1.

All the relevant processes detailed in sections 3 and 4 between the seven levels are taken into account (full resolution): radiative de-excitation, collisional electronic excitation and de-excitation, radiative and dielectronic recombination, photo-excitation and induced emission (between  $^3S_1$  and  $^3P$  levels).

We considered a broad range of densities ( $n_e$ ) and radiation temperatures ( $T_{rad}$ ) calculated for photo-excitation between the  $^3S$  level and the  $^3P$  levels and a number of electron temperatures ( $T_e$ ). As well, we considered different values of the dilution factor of the radiation field ( $W$ ) which could be used either for hot late-type stars or O, B stars.

We display the  $G(T_e)$  line intensity ratios, from Tables 4 to 9, for the six ions, for five values of electron temperature ( $T_e$ ) including the temperature of maximum line formation for the He-like lines (cf. Mewe et al. 1985); and for two or more values of the radiation temperature ( $T_{rad}$ ), and several values of  $n_e$ . As one can note the ratio  $G$  is as expected sensitive to  $T_e$ , while it is almost insensitive to the exact values of  $n_e$  and  $T_{rad}$ . The *resonance* line becomes sensitive at high density due to the depopulation of the  $1s2s^1S_0$  level to the  $1s2p^1P_1$  level (see Gabriel & Jordan 1972). Since the sum  $z + (x + y)$  is a constant or almost constant, the value of  $G$  is independent of the exact value of the dilution factor ( $W$ ). Here the calculations were done for dilution factor  $W=1/2$ .

Finally, we display the  $R(n_e)$  line intensity ratios for the six ions, in Tables 10 to 69, for the same values

<sup>5</sup> Tables 4 to 69 are only available in electronic form at the CDS via anonymous ftp to cdsarc.u-strasbg.fr (130.79.128.5) or via <http://cdsweb.u-strasbg.fr/cgi-bin/qcat?J/A+A/>.

of electron temperature ( $T_e$ ) and much more values of radiation temperature ( $T_{rad}$ ), and for three values of the dilution factor of the radiation field  $W=0.5, 0.1, 0.01$ .

Since as said previously in §4.3, the contribution of the blended dielectronic satellite lines depends on the spectral resolution, we give the values of  $R$  and  $G$  for Ne IX, Mg XI, and Si XIII, for four specific values of spectral resolutions (FWHM): RGS-1 at the first order (i.e.  $\Delta\lambda=0.073, 0.075$  and  $0.078\text{Å}$  for Ne IX, Mg XI and Si XIII respectively), LETGS (i.e.  $\Delta\lambda=0.05\text{Å}$ ), HETGS-MEG (i.e.  $\Delta\lambda=0.023\text{Å}$ ), and HETGS-HEG (i.e.  $\Delta\lambda=0.012\text{Å}$ ). In the cases where the differences ( $<1\%$ ) are negligible between two or more spectral resolutions, we display the results together (e.g. RGS and LETGS).

## 6. Conclusions

For the first time, thanks to the new generation of X-ray satellites, *Chandra* and *XMM-Newton* the diagnostics based on the line ratios of He-like ions could be used for powerful extra-solar plasma diagnostics (Warm Absorber in AGNs, stellar coronae, ...). These diagnostics are one of the keys for a better understanding of the solar-stellar connection: heating of the coronae, magnetic activity, etc. In this work, we have calculated the line ratio  $R$  and  $G$  which allow, respectively electron density and temperature diagnostics. These calculations are based partly on the previous work of Porquet & Dubau (2000) and on different improvements of atomic data (see §4).

We have tabulated the results adapted for the different spectral resolutions of the spectrometers on board of *Chandra* and *XMM-Newton* for parameter ranges which correspond as much as possible to most cases of stellar coronae (hot-late type star, O B stars...).

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## Appendix A: Atomic data for the blended dielectronic satellite lines with $n=2, 3, 4$ .

We report in this appendix the atomic data related to the dielectronic satellite lines, calculated in this work for  $Z=10, 12$ , and  $14$ , blended with one of their parent lines: *forbidden*, *intercombination*, and *resonance*.

The satellite line wavelengths and intensities have been obtained using a set of computer codes developed partly in University-College-London (SUPERSTRUCTURE: Eissner, Jones, Nussbaumer 1974) and in Meudon Observatory (AUTOLSJ: TFR group, Dubau J., Loulergue M. 1981). Multiconfigurational-wavefunctions are calculated in a "scaled" Thomas-Fermi-Dirac-Amaldi potentials, depending on linear scaling parameters ( $\lambda_s, \lambda_p, \lambda_d \dots$ ) different for  $l$ -orbitals, which are obtained through a self-consistent variational procedure on the energy sum of the first lowest (SL) terms. In SUPERSTRUCTURE, the level energies and the radiative probabilities are calculated in the relativistic Breit-Paul hamiltonian approach, which gives fine-structure bound and autoionizing levels. In the AUTOLSJ code, the autoionization probabilities are derived in the Distorted-wave approximation, using the same wavefunctions as in SUPERSTRUCTURE. For the present calculations, the following configuration were used :  $1s^2nl$ ,  $1s2snl$ , and  $1s2pnl$  for  $n = 2, \dots, 5$  and  $0 \leq l \leq n - 1$ .

The wavelengths of the dielectronic satellite lines calculated here should be compared to the "reference" wavelengths used in the Jacques Dubau's calculations respectively for Ne IX, Mg XI, and Si XIII,  $\lambda_w=13.4658, 9.1740, 6.6482 \text{ \AA}$ ,  $\lambda_y=13.5774, 9.2395, 6.6903 \text{ \AA}$ ,  $\lambda_x=13.5774, 9.2358, 6.6865 \text{ \AA}$ ,  $\lambda_z=13.7216, 9.3219, 6.7420 \text{ \AA}$ . One can notice that these wavelengths are not identical to the wavelengths of Vainshtein & Safronova (1978) used in the calculation of the line ratios  $R$  and  $G$ , tabulated in Table 1. Then in order to determine which dielectronic satellite lines are blended with one of the parent lines (*forbidden*, *intercombination*, and *resonance*), one should take into account the shift of the satellite line compared to the wavelengths chosen for the parent lines in the calculation of  $R$  and  $G$ .

The values of  $E_s$ , which is the energy of the satellite level  $s$ , used in this calculation are well reproduced using formula (29).

In tables<sup>6</sup> A.1, A.2, and A.3, the dielectronic satellite lines  $n=2$ , for  $Z=10, 12$ , and  $14$ , respectively are reported. In tables A.4, A.5, and A.6, the dielectronic satellite lines  $n=3$ , and  $4$ , for  $Z=10, 12$ , and  $14$ , respectively are reported.

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<sup>6</sup> Tables A.1 to A.6 are only available in electronic form.