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Improved Line Ratio Calculations for He-like Ions

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Abstract.
Helium-like density and temperature diagnostics, since more than three decades applied to the Sun, have now become a powerful tool in the analysis of the high-resolution Chandra and XMM-Newton X-ray spectra. Therefore, we have revisited the calculation of the ratios R=f/i and G=(f+i)/r of the resonance **r** ($1s^2\,{}^1S_0$ – $1s2p\,{}^1P_1$), intercombination **i** ($1s^2\,{}^1S_0$ – $1s2p\,{}^3P_{2,1}$), and forbidden **f** ($1s^2\,{}^1S_0$ – $1s2s\,{}^3S_1$) "triplet" lines of the He-like ions C V, N VI, O VII, Ne IX, Mg XI, and Si XIII, taking into account all relevant processes and improved atomic data. The first calculations have been done for optically thin plasmas in collisional ionization equilibrium (e.g., stellar coronae). The influence of an external radiation field on the depopulation of the upper level of f is considered which can be important for hot OB or F stars (e.g., ζ Puppis, Procyon, and Algol). In preparation are updated calculations for photo-ionized and hybrid plasmas (e.g., warm absorber in AGNs), and for transient ionization plasmas (young SNRs).

1. Introduction

More than three decades since Gabriel and Jordan (1969) introduced the technique to determine from the ratios R and G electron density and temperature of the Solar corona, many calculations have been done for a plasma in collisional ionization equilibrium (CIE) (for references, see Porquet, Mewe et al. 2001). With the advent of a new generation of X-ray satellites (Chandra and XMM-Newton) X-ray spectroscopy with unprecedented spectral resolution and high S/N is now possible. The analysis of the He-like "triplets" is a powerful tool in the analysis of the high-resolution spectra of a variety of plasmas such as CIE plasmas (e.g., stellar coronae), X-ray photo-ionized equilibrium (PIE) plasmas (e.g., AGNs), or transient non-equilibrium ionization (NEI) plasmas (e.g., SNRs). For reviews, e.g., Mewe (1999) (CIE, NEI) and Liedahl (1999) (PIE).

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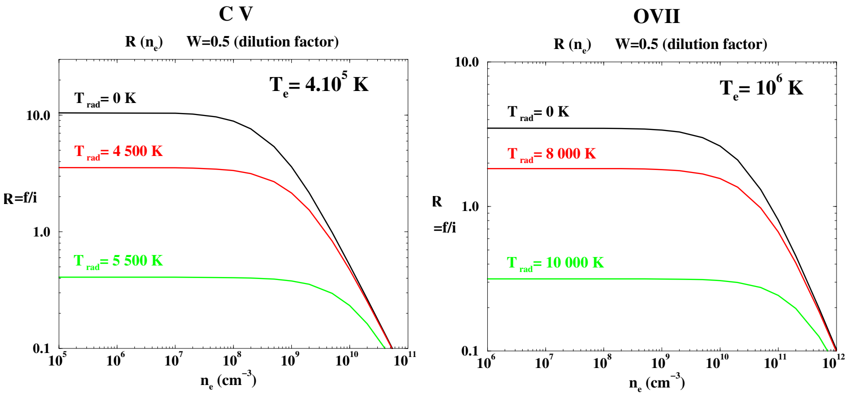

Figure 1. Ratio R=f/i in dependence of stellar radiation field for C V and O VII. Note that e.g., for O VII a radiation field with effective temperature of 10^4 K can mimic a density of about 3 10^{11} cm^{-3}.

Recently, Porquet & Dubau (2000) made the first calculations to extend the theory to photo-ionized plasmas and "hybrid" plasmas (photo-ionization from an external radiation source plus collisional ionization from an internal source). These calculations make use of the electron collisional excitation data from Sampson et al. (1983) for $n > 2$ and from Zhang & Sampson (1987) for $n = 2$ which include resonance effects at threshold. The calculations take into account radiative and dielectronic recombination processes and radiative cascades from upper levels both for recombination and excitation. The warm absorber (WA) present in the central part of Active Galactive Nuclei is a possible example of a hybrid plasma. The calculations have already been applied to the analysis of several Seyfert galaxies (for references, see Porquet, Mewe et al. 2001), e.g., to the Chandra-LETGS spectrum measured by Kaastra et al. (2000) which shows a nice O VII triplet that was used to constrain the electron density in the WA. Based on the first calculations by Porquet & Dubau (2000) we will proceed in a series of papers with the revision of the calculation of the R and G ratios and give extended results in a databank to allow a detailed analysis of the various Chandra and XMM-Newton spectra. In the first paper of this series (Porquet, Mewe et al. 2001) we have considered optically thin CIE plasmas and updated the radiative transition probabilities with published experimental values (which reduces R by about 20% (or 10%) for C V (or N VI) but has no influence for higher Z), considered the influence of a radiation field, the possible contribution of unresolved dielectronic recombination satellites, and optical depth effects. In two later papers we will consider photo-ionized plasmas (Porquet, Kaastra et al. 2002) in which the effect of DR satellites becomes more important, and transient ionization plasmas (Mewe, Kaastra et al. 2002).
In the following sections we consider briefly four important effects on the line ratios: effects of an external radiation field, of blended dielectronic recombination (DR) satellite lines, optical depth, and transient ionization, respectively.

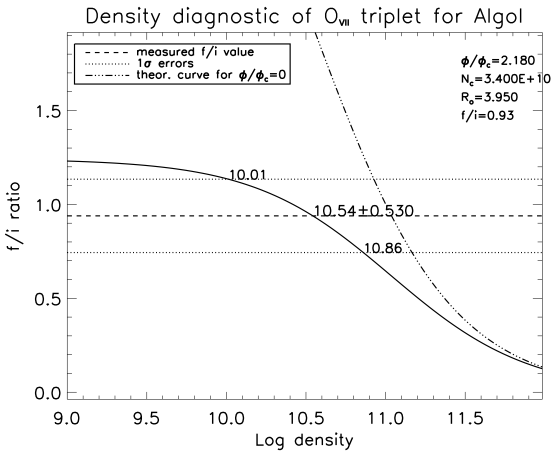

Figure 2. Derived electron density in the corona of the K-component in the Algol binary from Chandra-LETGS measurements, taking into account the possible influence of the strong radiation field of the hot primary B-star. Dashed-dotted curve: zero radiation field; solid curve: radiation field with dilution factor $W \simeq 0.01$.

2. Radiation Field Influence

A strong radiation field can mimic a high density if the photo-excitation 2 $^3\mathrm{S}_m$ level (f line) $\rightarrow$ 2 $^3\mathrm{P}_{p_k}$ level (i lines) exceeds the electron collisional excitation. The rate of photo-absorption (in s^{-1}) in a stellar photospheric radiation field with effective BB radiation temperature T_{rad} is (Mewe & Schrijver 1978a):

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

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

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

• W=1/2 (close to the stellar surface, $r = r_*$); e.g., Capella and Procyon where radiation effects are important for C V and N VI but not for O VII (Ness et al. 2001a). Fig. 1 shows that radiation effects become important for C V, N VI, and O VII for $\mathrm{T}_{\mathrm{rad}} \gtrsim$(5-10) 10^3 K and for higher-Z ions when $\mathrm{T}_{\mathrm{rad}} \gtrsim$ few 10^4 K, e.g, hot O stars like ζ Puppis (Kahn et al. 2001, Cassinelli et al. 2001).
We note that for O VII in the low-density limit at T=1 MK R=3.5 (see Fig. 1), whereas Smith et al. (2001) give for the same case a value of 4.1 (17% higher). This is most probably due to the fact that Smith et al. use for the excitation the data from Kato & Nagasaki (1989) that overestimate for the forbidden line the effect of threshold resonances due to the neglect of radiative effects which

were taken into account by Zhang & Sampson (1987) (whose data we use) (see Dubau (1994) and Dubau, private communication).
• $W << 1/2$ (radiation originates from another star at larger distance); e.g., the binary Algol, where the K-star is irradiated by the B-star (Fig. 2, Ness et al. 2001b,c).
We note that the dependence of R on density and radiation flux can be written in a handsome way as given by Blumenthal & Tucker (1972):

$$R(N_{\rm e}) \;=\; f/i \;=\; \frac{R_{\rm o}}{1+\phi/\phi_{\rm c}+N_{\rm e}/N_{\rm c}}, \tag{3}$$

where $\phi \equiv B_{mp_k}$ is photo-excitation rate $2\ ^3{\rm S}_m \rightarrow 2\ ^3{\rm P}_{p_k}$, and the quantities $R_{\rm o}$, $\phi_{\rm c}$, and $N_{\rm c}$ depend only on atomic parameters and electron temperature.

3. Blended Dielectronic Recombination Satellite Line Contributions

At T=T_m, the maximum line formation temperature, the dielectronic recombination (DR) satellite contribution is for Ne IX, Mg XI, and Si XIII (low-density limit, $T_{\rm rad}$=0 K, and ionization balance from Mazzotta et al. (1998)): ΔR (or ΔG): $\sim$ 1%(9%), 2%(5%), and 5%(3%), respectively.
However, for photo-ionized plasmas where recombination prevails and the temperature is much lower (e.g., T$\lesssim$0.1T_m), the effect on R and G can be much bigger since $I_{sat}/I_{He} \propto T^{-1} e^{(E_{r,i,f}-E_{sat})/kT}$. Hence, DR $n=2$ satellites can influence the forbidden line and $n>2$ satellites the resonance and intercombination lines also in low-Z ions (e.g., O VII) (see Porquet, Kaastra et al. (2002) for photo-ionized plasmas). Fig. 3 shows the increasing influence of DR satellites for decreasing temperature.

For very high density $n_{\rm e}$ the contribution of the blended DR satellite lines to the forbidden and intercombination lines leads to a ratio R which tends to $satf/sati$ (where satf and sati are the contributions of blended satellite lines to the forbidden and intercombination lines, respectively), hence decreases much slower with $n_{\rm e}$ than in the case where the contribution of the blended DR satellites is not taken into account.

4. Optical Depth Effects

If the optical depth of the resonance line (r) is not taken into account, the calculated ratio G could be overestimated (inferred temperature underestimated) in the optically-thin approximation. This has been discussed by Porquet, Mewe et al. (2001) and will be estimated with an escape-factor method, e.g., for the case of a warm absorber (WA) in an AGN (see Porquet, Kaastra et al. 2002).

5. Transient Ionization Effects

Recently, high-resolution XMM-RGS X-ray spectra were obtained for two bright supernova remnants (SNRs) located in the Small Magellanic Cloud (1E 0102-72.3 (Rasmussen et al. 2001) and N132D (Behar et al. 2001)). These sources are

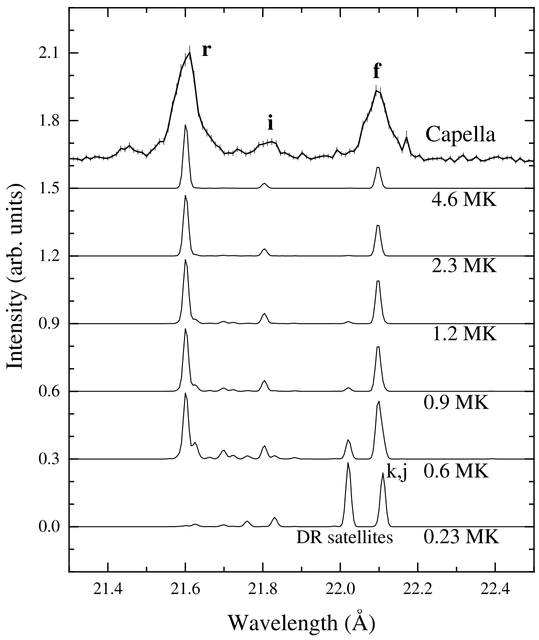

Figure 3. Measured XMM-RGS O VII triplet in Capella compared with calculated spectra for different electron temperatures. At high temperature (e.g., 2.3 MK $\simeq T_m$) the O VII line triplet is formed by electron collisional excitation. At decreasing temperature the influence of DR satellites increases until at very low temperature (0.23 MK $\simeq 0.1 T_m$, as common in photo-ionized plasmas), the O VI DR satellites j and k at 22.129 and 22.125 Å, respectively., dominate the forbidden line f at 22.101 Å for the XMM-RGS spectral resolution (0.05 Å). Features at 22.024 and 22.025 Å are q and r innershell excitation+DR satellites and features between 21.63 & 21.83 Å are higher $n > 2$ DR satellites (modified Fig. 3 from Audard et al. 2001).

expected to be in a highly transient state with strong effects of non-equilibrium ionization, e.g., innershell ionization of the Li-like ion which occupies for 3/4 (or 1/4) the upper level of the forbidden line (or the two-photon process), resulting in an enhancement of the forbidden line in a transient ionizing plasma as was already shown by Mewe and Schrijver (1978b). E.g., for iron:

$$\text{FeXXIV } 1s^2 2s\ ^2S_{1/2} + e^- \longrightarrow \text{FeXXV } 1s2s\ ^3S_1 \text{ (or } ^1S_0) + 2e^- .$$

Measured EBIT spectra in the 0–20, 40–60, and 80–1000 ms time intervals show good agreement with the predictions by Mewe & Schrijver (1980) for their model A for a shock-heated plasma at times 0.1, 6, and 10 s after the passage of the shock (Decaux et al. 1997). In the beginning phase lines formed by innershell excitation/ionization are strongly enhanced (e.g., the forbidden line f is then comparable or even stronger than the resonance line r).

Calculations by Mewe, Kaastra et al. (2002) with the currently publicly available Utrecht spectral code SPEX (Kaastra et al. 1996) are in preparation.

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