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Influence of UV Radiation Fields on Density Diagnostics with He-like Triplets

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Abstract. Spectroscopic density diagnostics based on He-like triplets are routinely used to investigate the solar corona. With the new instrumentation onboard Chandra and XMM this method of analysis can also be applied to stellar coronae.

In collision-dominated plasmas the forbidden line f ($1s2s\,^3S_1 \rightarrow 1s^2\,^1S_0$), disappears at high densities, and the intercombination line i ($1s2p\,^3P_{2,1} \rightarrow 1s^2\,^1S_0$) increases at higher densities at the expense of the forbidden line. Therefore, the ratio f/i is used as a sensitive indicator of electron density. However, depopulation of the forbidden line compared to the intercombination line, is not always an indicator for high densities, it might also indicate that the depopulation of the forbidden line level ($1s2s\,^3S_1 \rightarrow 1s2p\,^3P_{2,1}$) is due to a UV radiation field instead of the collisions in a high-density plasma.

We illustrate this effect with IUE measurements of Capella, Procyon, Algol and α Cen A and α Cen B and a simulation showing the trend of the radiation fields when regarding stars with different surface temperatures. Focusing on the triplets of C V, N VI, O VII and Ne IX, we show that the radiation fields can have significant influence on the density analysis of the low-Z He-like ions of C, N and O. We present Chandra LETGS measurements and calculate the densities accounting for the measured radiation fields and neglecting them. The sources of the UV radiation are assumed to be the respective stellar surfaces, but in the case of Algol the radiation is supplied by the companion B star. A detailed investigation of whether the observed part of Algol's corona is actually illuminated by the radiation field of the B star, is necessary.

1. Introduction

The method of using He-like triplets for determination of electron densities in high temperature plasmas has been developed by Gabriel & Jordan (1969). It has been refined by, e.g., Blumenthal et al. (1972), Mewe & Schrijver (1978),

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Pradhan et al. (1981), Pradhan & Shull (1981), and Pradhan (1982). The method has been exploited for the Sun quite extensively, but was not accessible for other stars until the advent of the high-resolution spectrometers on Chandra and XMM. A recent revision of the He-like line ratio technique has been carried out by Porquet et al. (2001) (see also Mewe et al. 2001).
In this paper we will explain the principle of how the lines of He-like triplets react to density effects and how UV radiation can interfere with these effects. We will then show that the radiation field parameters for the density diagnostics can be measured. Some LETGS measurements will be introduced in Sect. 4 where the influence of radiation fields on the low-density limit is shown. We will finally give an impression in which cases UV radiation fields must be measured and included in the analysis.

2. Atomic Physics of He-like Triplets

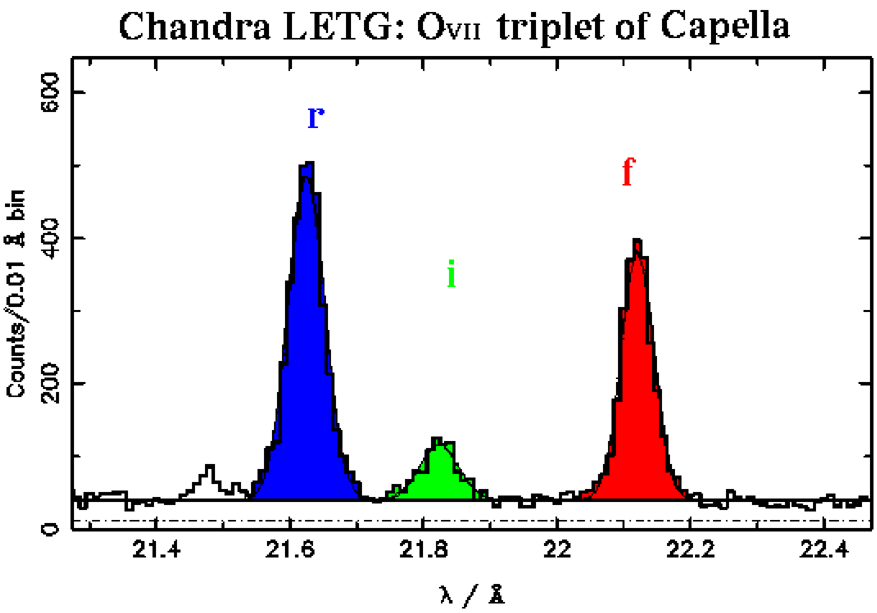

Figure 1. LETGS measurement of Capella's corona: O VII triplet.

He-like ions are ions consisting of a core with two electrons. The most prominent lines emitted by He-like ions are the He-like triplets. In Fig. 1 we show a measured spectrum of the O VII triplet for Capella. The three important transitions resonance r ($1s2p^1P_1$), intercombination i ($1s2p^3P_1$) and forbidden f ($1s2s^3S_1$) are denoted. The ground state is $1s^2\,{}^1S_0$. The term diagram with corresponding colors as in Fig. 1 is shown in Fig. 2.

Most important for the density diagnostics is the transition between f and i, thus $1s2s^3S_1 \rightarrow 1s2p^3P_1$. In low-density plasmas this transition should not occur. In higher densities this excitation can be triggered by collisions, because

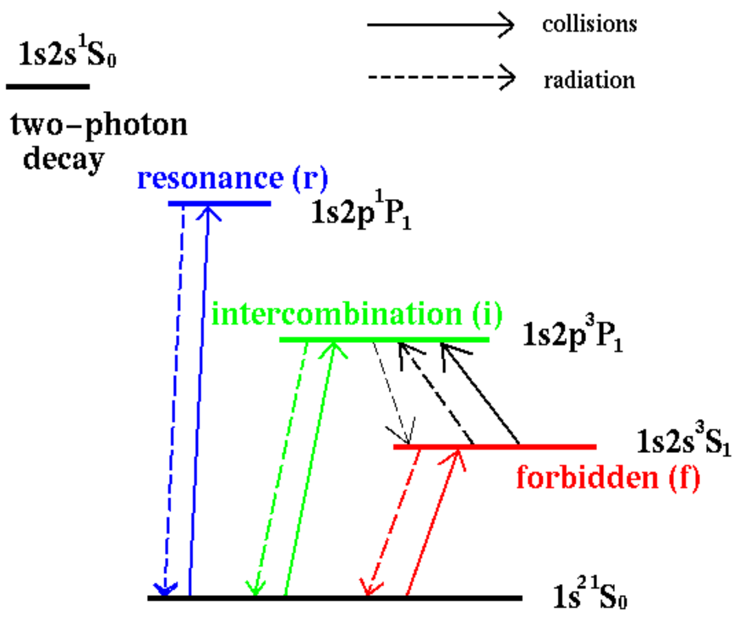

Figure 2. Simplified term diagram of He-like triplets.

the $1s2s^3S_1$ level is metastable, thus allowing sufficient time for suffering from collisions. In comparison with the low-density case, more de-excitations via the intercombination level will be encountered, thus the intercombination line will become stronger, and the forbidden line will become weaker. The ratio f/i is therefore a very sensitive density indicator.
But, as can also be seen from Fig. 2, this decisive transition can also be excited by photons with the energy dE = E_f-E_i. dE lies in the UV range for the commonly used He-like ions. In order to decide whether photons with the respective energy are supplied one needs to look out for strong UV fields in the vicinity of the emitting plasma. When investigating coronal plamas the stellar surface is a candidate, but we will find that even companion stars are also good candidates for the sources of significant UV radiation.

As can be seen from Fig. 2 the influence from a radiation field should compete with collisions on the same level. A term accounting for the radiation field has first been included in the density diagnostics by Gabriel & Jordan (1969). In our analysis we use the relation

$$\frac{\mathrm{f}}{\mathrm{i}} = \frac{R_0}{1 + \phi/\phi_c + n_e/N_c} \tag{1}$$

with R_0 the low-density (and low radiation field) limit, ϕ/ϕ_c the radiation term, n_e the desired electron density, and N_c the density where f/i falls to half its low-density value. Densities are derived by just comparing measured f/i values with the errors with the theoretical curve represented by the right side of Eq. 1.

UV radiation fields are accounted for by using $\phi/\phi_c \neq 0$. The atomic parameters R_0 and N_c are provided by, e.g., Pradhan & Shull (1981).

3. Measuring the Influence of UV Radiation Fields

From Eq. 1 it can be seen that the radiation field is represented by the term ϕ/ϕ_c in the analysis. The task is now to find adequate values for ϕ/ϕ_c. This is done by first finding the wavelength for the transition f $\rightarrow$ i (cf. Mewe & Schrijver 1978) for each individual ion. The values used in our analysis are listed in Tab. 1.

Table 1. Wavelengths for the transition $1s2s\,^3S_1 \rightarrow 1s2p\,^3P_{2,1}$ for C V, N VI, O VII and Ne IX. Also ionization potentials used in Eqs. 6 and 7 are listed.

	C V	N VI	O VII	Ne IX
$\lambda_{\mathrm{f}\rightarrow\mathrm{i}}/\text{Å}$	2272	1900	1630	1266
$I_{\mathrm{pot}}/\mathrm{eV}$	392.1	552.1	739.3	1195.3

The level $1s2p\,^3P_{2,1}$ is split up into three levels, but the mean value of the three transition energies can be used. A good reference is the use of databases, e.g. the NIST[1] server or the Kurucz[2] line list.
The next step will be to find a flux from the star at the respective wavelength. For our analysis we used IUE data, obtained from the IUE[3] archive. But also the HST-STIS[4] archive can be used. The measured flux can be converted into an intensity with

$$I_\lambda = F_\lambda \frac{d^2}{R^2} \frac{1}{2\pi(1-\frac{\epsilon}{2})}\,, \tag{2}$$

with the distance of the star d, the stellar radius R, and the linear limb darkening coefficient ϵ. ϵ can be obtained from, e.g., Díaz-Cordovés et al. (1995). The thus obtained intensity can be compared with a set of Planck curves

$$I_\lambda = W \frac{2hc^2}{\lambda^5} \frac{1}{\exp\left(\frac{hc}{\lambda k T_{\mathrm{rad}}}\right) - 1} \tag{3}$$

in order to infer a radiation temperature T_{rad}. The dilution factor W is calculated with

$$W = \frac{1}{2}\left[1 - \left\{1 - \left(\frac{r_\star}{a}\right)^2\right\}^{1/2}\right] \tag{4}$$

[1]http://physics.nist.gov/cgi-bin/AtData/lines_form

[2]http://cfa-www.harvard.edu/amdata/ampdata/kurucz23/sekur.html

[3]http://ines.laeff.esa.es/cgi-ines/IUEdbsMY

[4]http://archive.eso.org/archive/hst/

(Mewe & Schrijver 1978) with the stellar radius $r_\star$, and the distance a between the UV source and the corona. For the case of the stellar surface to be the UV source, $a = r_\star$, thus $W = 1/2$ is commonly used.
The correct Planck curve u_ν is used to calculate the term ϕ/ϕ_c with

$$\frac{\phi}{\phi_c} = \frac{3(1+\mathrm{F})c^3}{8\pi h\nu^3} \frac{\mathrm{A}(2\,^3\mathrm{P} \rightarrow 2\,^3\mathrm{S})}{\mathrm{A}(2\,^3\mathrm{S}_1 \rightarrow\; 1\,^1\mathrm{S}_0)} u_\nu \tag{5}$$

(Blumenthal et al. 1972) with $\phi_c = \mathrm{A}(2\,^3\mathrm{S}_1 \rightarrow\; 1\,^1\mathrm{S}_0)/(1+\mathrm{F})$, transition probabilities $\mathrm{A}(j \rightarrow k)$, and u_ν the spectral energy density at the appropriate $2\,^3\mathrm{P}_1 \rightarrow\; 2\,^3\mathrm{S}_1$ frequency ν. The factor 3 is the ratio of the statistical weights of the levels $2\,^3\mathrm{P}$ and $2\,^3\mathrm{S}$. F is approximated by Blumenthal et al. (1972) through

$$\mathrm{F}(\xi) = \frac{3\xi\mathrm{H}(\xi)exp(\xi/4) + 1.2\xi + 2\mathrm{H}(\xi) + 2}{3\xi exp(\xi/4) + 0.6\xi\mathrm{H}(\xi) + \mathrm{H}(\xi) + 1}, \tag{6}$$

where

$$\mathrm{H}(\xi) = \frac{\mathrm{C}(1\,^1\mathrm{S} \rightarrow\; 2\,^3\mathrm{S})}{\mathrm{C}(1\,^1\mathrm{S} \rightarrow\; 2\,^3\mathrm{P})}, \tag{7}$$

with $\xi = I_{\mathrm{pot}}/kT_{\mathrm{rad}}$ and the collisional excitation rate coefficients $\mathrm{C}(j \rightarrow k)$. Values for the ionization potentials I_{pot} for each ion are given in Tab. 1 (cf., e.g., Pradhan & Shull 1981). Collisional excitation rate coefficients $\mathrm{C}(j \rightarrow k)$ can be taken from Pradhan et al. (1981). The described method has been applied by Ness et al. (2001) for the ions C V, N VI, and O VII for the stars Capella and Procyon.

4. Application of the Method

The method described in Sect. 2 has been applied to the stars Capella, Procyon, and Algol. In Fig. 3 the theoretical curve from Eq. 1 is plotted in comparison with the f/i value measured with Chandra LETGS for Algol. The atomic parameters for O VII from Pradhan & Shull (1981) were used. From the measured UV flux $f = 2.2\,10^{-9}$ erg/cm^2/s/Å we derive a radiation temperature of 12700 K. Since this temperature is not typical for a K star (the most probable X-ray source in the Algol system) it is rather to assume, that the UV radiation is provided by the companion B star. We therefore applied a dilution factor $W = 0.01$, accounting for the distance (a=14.6 $\mathrm{R}_\odot$) and the radius (R=3.5 $\mathrm{R}_\odot$) of the companion star for calculating the radiation term $\phi/\phi_c = 2.18$. Despite of the much smaller dilution factor, the O VII triplet is only in the case of Algol really influenced by the radiation field. For Procyon and Capella it can be neglected. This can be seen from Tab. 2, where all steps are recorded according to Eqs. 2 to 7 for the stars Capella, Procyon, and Algol. As can be seen, Capella has the lowest temperatures, while the F star Procyon is much hotter and Algol's B star is the hottest star.

In Tab. 3 we present the results from our density diagnostics with and without (ϕ/ϕ_c=0) radiation fields. The f/i ratios have been obtained with Chandra LETGS. As can be seen, the densities are overestimated when leaving out the effects of radiation fields. But in the case of Algol, an exact estimate is more

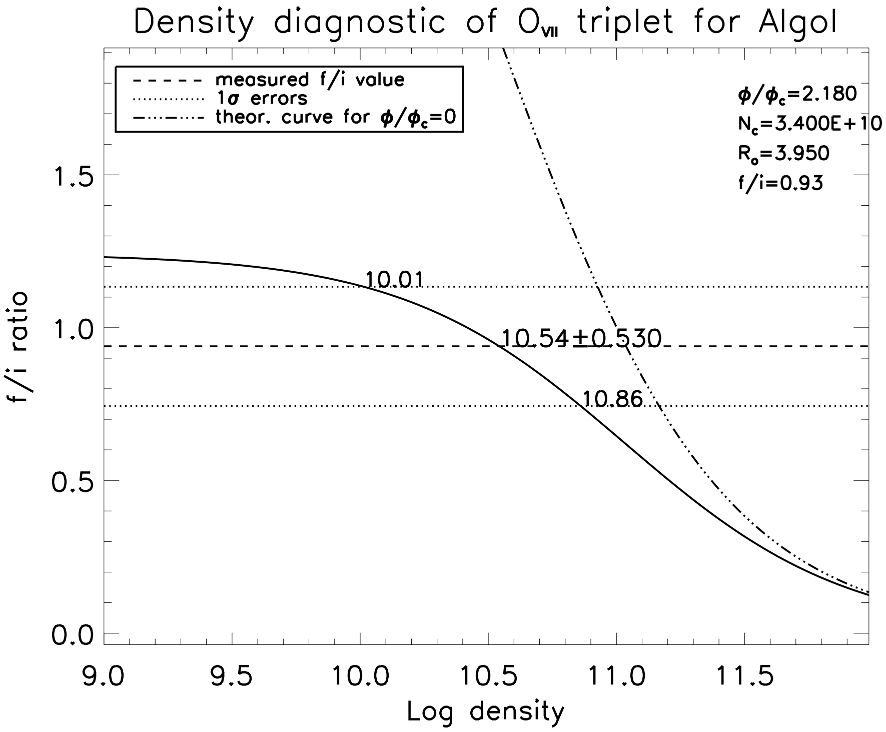

Figure 3. Inferring densities from the line ratio f/i (broken line: Chandra LETGS measurement, with errors dotted) for the example of Algol. The term $\phi/\phi_c = 2.18$ was measured with IUE, and the theoretical curves given with (solid line) and without (line-dotted line) radiation term (i.e. ϕ/ϕ_c=0).

complicated depending on the chosen geometry, since only half of the corona is illuminated by the companion B star, and the influence of the UV radiation depends on how much of the illuminated corona we actually observe. This consideration is discussed in detail by Ness et al. (2001a) and Ness et al. (2001b).

5. Results

5.1. The low-density limit

In Eq. 1 the low-density limit R_0 is introduced as an atomic parameter representing the ratio f/i to be measured when no transitions f $\rightarrow$ i take place, thus $\phi = 0$ and $n_e = 0$. For the purpose of density diagnostics the low-density limit puts a constraint on the range of measurable densities. When significant radiation fields influence the density diagnostics, this does not necessarily mean that no density diagnostics can be performed, but the range of measurable densities will be reduced. This is illustrated with Fig. 4, where the reduced low-density limit $R_0/(1 + \phi/\phi_c)$ is plotted versus the atomic number Z. The black curve represents the isolated values R_0 taken from Pradhan & Shull (1981).

Table 2. Investigation of the influence of the stellar radiation fields for Capella ([1]), Procyon ([2]) and Algol ([3]). Measured fluxes from the IUE satellite F_λ are converted to intensity I_λ taking into account limb darkening effects using $\epsilon = 0.83$ (Capella), $\epsilon = 0.724$ (Procyon) and $\epsilon = 0.44$ (Algol). The dilution factor is 0.5 except for Algol ($W = 0.01$).

	C V	N VI	O VII	Ne IX
$\frac{F_\lambda}{(10^{-10}\frac{\mathrm{ergs}}{\mathrm{cm^2\,s\,Å}})}$				
1	0.2 ± 0.05	0.12 ± 0.05	0.025 ± 0.005	
2	1.5 ± 0.4	0.7 ± 0.3	0.06 ± 0.03	
3		20 ± 2	22 ± 2.2	20 ± 6
$\frac{I_\lambda}{(10^{4}\frac{\mathrm{ergs}}{\mathrm{cm^2\,s\,Å\,strd}})}$				
1	1.98 ± 0.5	1.19 ± 0.3	0.25 ± 0.5	
2	21 ± 5	9.8 ± 4	0.84 ± 0.4	
3		9100 ± 910	9980 ± 100	9100 ± 270
$T_{\mathrm{rad}}/\mathrm{K}$				
1	4590 ± 100	4980 ± 150	5030 ± 50	
2	5530 ± 150	5780 ± 200	5410 ± 300	
3		12060 ± 190	12710 ± 190	13690 ± 560
ϕ/ϕ_{c}				
1	2.54 ± 0.86	0.2 ± 0.1	0.003	
2	26.67 ± 9.3	1.58 ± 0.84	0.01 ± 0.015	
3		24.74 ± 2.41	2.18 ± 0.29	0.1 ± 0.03

As can be seen from Fig. 4 the influence of the radiation field is only important for C V and N VI for all the stars except for Algol. For the ions with higher Z the influence of the radiation fields becomes smaller. For Ne IX (Z=10) a measurable influence is perhaps only encountered in the case of Algol.

5.2. Densities

In order to demonstrate the effect of radiation fields on the results of the density diagnostics, we calculated the expected densities for the ions C V, N VI, O VII and Ne IX assuming a hypothetically measured ratio f/i=3.0 (Fig. 5 upper panel) and a dilution fcator $W = 1/2$. The radiation field is given in terms of radiation temperatures. To give an orientation, the spectral types of stars corresponding to the temperatures are indicated. As can be seen from Fig. 5 (upper panel) the resulting densities are constant as long as the radiation temperatures are low. For higher radiation temperatures the densities calculated for f/i=3.0 are much smaller. This effect can be seen to be most severe for C V, while higher radiation temperatures can be tolerated for Ne IX.

The same procedure has been applied for a hypothetical measurement of f/i=1.0. As can be seen from Fig. 5 (lower panel) the obtained densities are higher and the results are less sensitive to high radiation temperatures. While in coronae with low densities (f/i=3.0) an F star can already harm the density diagnostics with O VII, the results in the density diagnostics are not influenced by the same radiation field in the case of a high-density plasma with f/i=1.0.

Table 3. Results of density diagnostics from Chandra LETGS measurements with and without radiation fields for the stars Capella, Procyon, and Algol. In addition the stellar parameters distance d, effective temperature $T_{\rm eff}$ and linear limb darkening parameter ϵ are given.

	Capella G1III/G8		Procyon F5IV-V		Algol K2IV/B8V	
d/pc	13		3.5		31	
$T_{\rm eff}$/K	5700		6530		4500/13000	
ϵ	0.83		0.724		0.44	
C V	f/i=1.48		f/i=0.48		*no detection*	
ϕ/ϕ_c	2.54	0	26.67	0	–	–
$\log(n_e)$	9.42 ± 0.21	9.66 ± 0.13	< 8.92	10.2 ± 0.12	–	–
N VI	f/i=1.78		f/i=1.33		f/i=0.21	
ϕ/ϕ_c	0.2	0	1.58	0	24.74	0
$\log(n_e)$	9.86 ± 0.12	10.09 ± 0.09	9.96 ± 0.23	10.27 ± 0.13	10.13 ± 0.93	11.16 ± 0.23
O VII	f/i=4.0		f/i=3.28		f/i=0.94	
ϕ/ϕ_c	0.003	0	0.01	0	2.18	0
$\log(n_e)$	<9.4	<9.4	<9.6	<9.6	10.54 ± 0.53	11.04 ± 0.13

6. Conclusions

From our analysis of the influence of UV radiation fields on the density diagnostics with He-like ions we conclude, that in the analysis of coronal plasmas it is important to keep this effect in mind. When leaving out the radiation field, one might obtain overestimated densities.
We have shown, that the radiation effects can be taken care of with the term ϕ/ϕ_c which again can be measured. With reliable measurements of ϕ/ϕ_c one can get improved densities. It has also been shown, that the influence of radiation fields on the density diagnostics are most severe for the low-Z ions C V and N VI, although for strong UV sources also O VII might be influenced. When investigating individual stars, one needs to take special care of this effect when dealing with hot stars with high $T_{\rm eff}$.
We want to point out, that the effect from UV radiation is only one major effect that might influence the density diagnostics. There are other effects like blended dielectronic satellite lines to each line of the triplets. This affects especially the high-Z ions like Ne IX, Mg XI, and Si XIII (Porquet et al. 2001). Also recombination from H-like ions can be important for photo-ionized plasmas or innershell ionization of Li-like ions in transient plasmas (Mewe et al. 2001).

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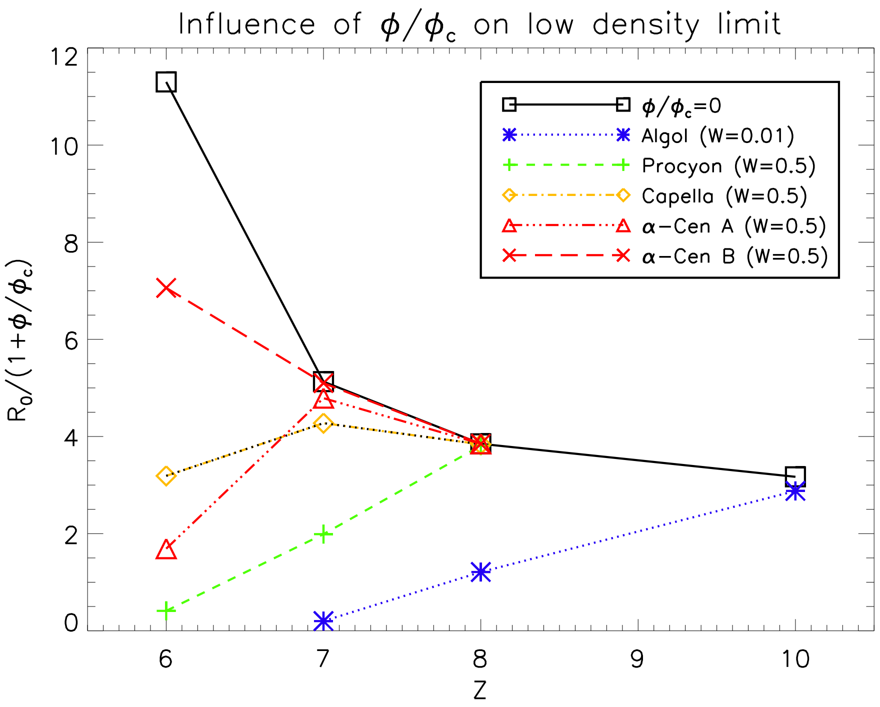

Figure 4. Influence of different radiation fields on the low-density limit restricting the density diagnostics. W is the dilution factor applied for the geometry of the stars. Plotted is the expected f/i ratio for the case $n_e = 0$ (cf. Eq. 1) versus atomic number Z.

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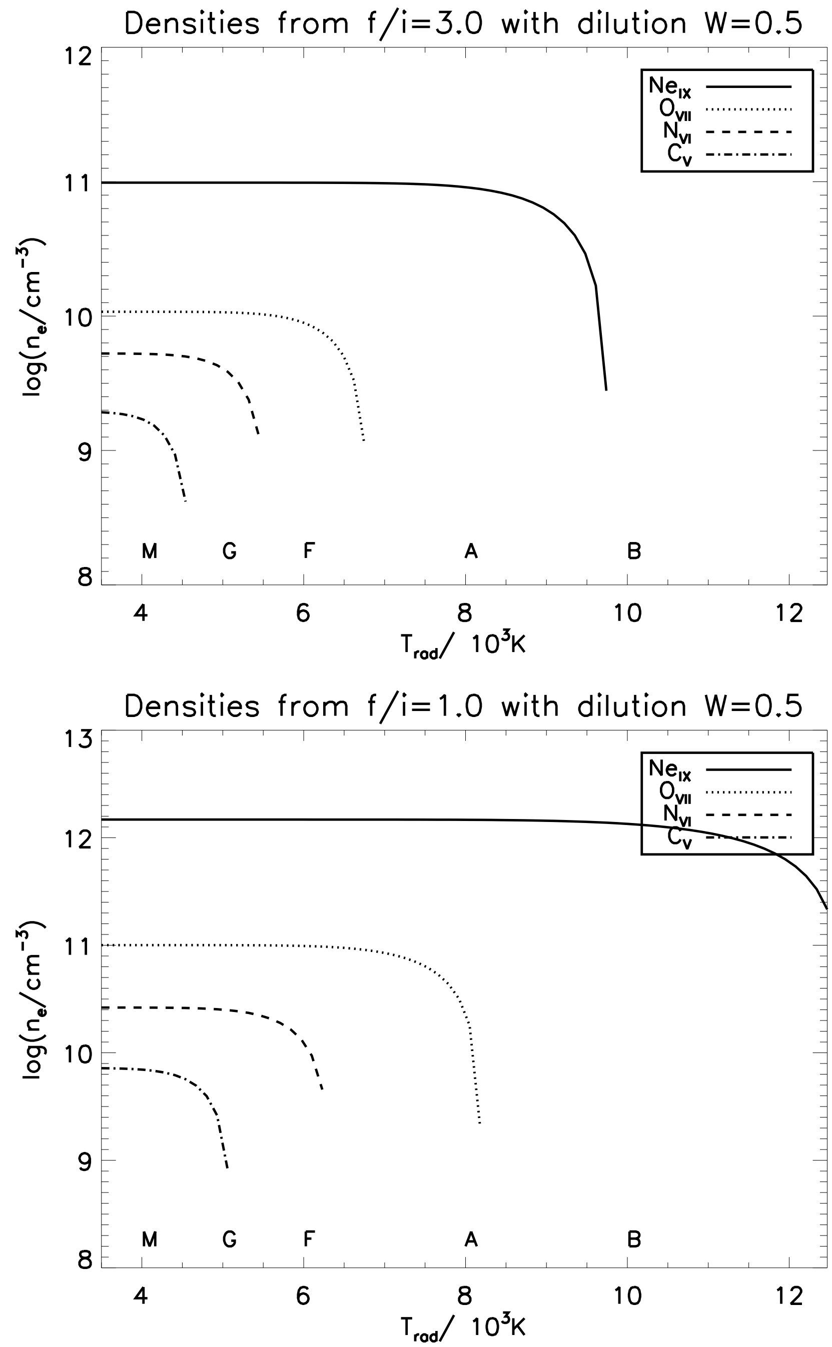

Figure 5. Simulation of derived densities for a hypothetic measurement of f/i=3.0 (upper panel) and f/i=1.0 (lower panel) as a function of radiation temperatures. To give an impression the spectral types M to B are given.