Non-LTE Model Atmospheres with Line Blanketing and Photon Loss

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Abstract. Photon loss from the He II λ303 transition was found to be an important process for Wolf-Rayet atmospheres. Here, I investigate whether photon loss is also important for O-star atmospheres. By studying the photon-loss effects on a model of an O5.5 supergiant, I find that there is a region around $\tau_R \simeq 0.1$ where the level populations are sensitive to the photon loss. However, the line profiles of the diagnostic lines do not show any changes, because they are formed in deeper layers than those affected by photon loss.

1. Introduction

Nowadays, line blanketing is a mandatory attribute of non-LTE model atmospheres for hot, luminous stars. This is not only true because of its influence on temperature structure and emergent radiation, but also because it is the same interaction that is responsible for the creation and acceleration of the radiation-driven mass loss. The method used for the models presented in this contribution is based on a Monte-Carlo opacity-sampling technique that is described in detail in Schmutz (1991) and Schaerer & Schmutz (1994). The advantage of the method is that it is cheap in terms of computer time; the disadvantage is that it only yields the property of the radiation field averaged over a given frequency interval, and therefore it is not possible to compare in detail the predicted blanketed emergent flux with observed spectra.

A special aspect of line blanketing is the interaction of transitions which are close in wavelength. It has been pointed out by Schmutz (1997) that this interference is crucial for the understanding of the ionization equilibrium in Wolf-Rayet atmospheres and, ultimately, for the understanding of the acceleration of their winds. In the application to Wolf-Rayet atmospheres it turned out that the line interactions resulted in a loss of photons from the He II λ303 transition, and therefore that process was termed 'photon loss'. There is no obvious reason why photon loss should be restricted only to Wolf-Rayet atmospheres; it may be of relevance whenever there are lines close in wavelength and one of the lines is optically very thick. It is just a matter of consulting a line list in order to realize that there are many relatively strong lines that potentially interact with the He II resonance transition under the conditions of atmospheres of 'normal' O stars. The present contribution investigates the effect of line blanketing in general, and in particular the effect of photon loss on model atmospheres of O stars.

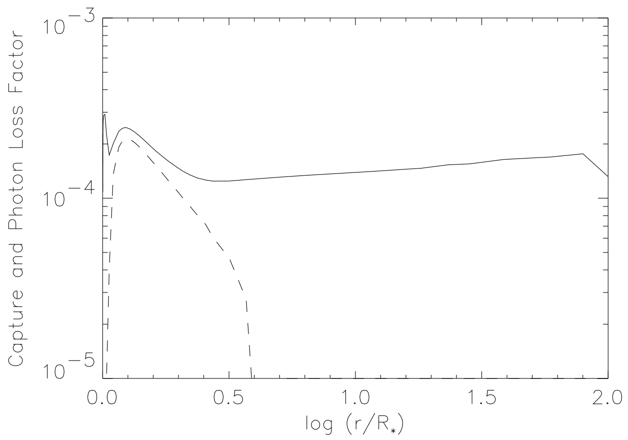

Figure 1. Capture factor, $f^{\rm cap}$, (full drawn line) and photon-loss factor, f^* (dashed). The photon-loss factor is negative for $r > 4R_*$.

2. The Effect of Photon Loss in O-Star Atmospheres

The effect of metal lines on the He II $\lambda303$ transition can be taken into account by modifying $\bar{J}^*$, the radiation field of the helium line evaluated in the *absence* of metal-line effects; this modified radiation field can be written as

$$\bar{J}^{\rm ph.l.}_{\lambda303} = (1 - f^*)\,\bar{J}^*_{\lambda303} \tag{1}$$

(Schmutz 1997). The factor f^*, the photon-loss factor, can be written as (Schmutz 1997, Eqn. A10):

$$f^* = f^{\rm cap} - \sum_i f^{{\rm m}_i}\,\frac{S^{{\rm m}_i}}{\bar{J}^*}\,, \tag{2}$$

where the factor $f^{\rm cap}$ gives the probability that a photon of the line radiation field is absorbed by a metal-line transition, and the second term gives the probability that a photon is contributed from metal transitions. It turns out that the first term, the capture factor $f^{\rm cap}$, can be calculated reliably without knowing the exact populations of the levels of the metal lines (Schmutz 1997, Eqn. A12), whereas the magnitude of second term depends sensitively on the ratios of the source functions of the metal transitions to the radiation field of the helium line. Under non-LTE conditions in the part of the atmosphere that is optically thin for continuum processes, it is very unlikely that the two terms have the same magnitude. Therefore, there will be either a photon loss with a factor that is well approximated by the (relatively reliable) capture factor, or there will be a gain of photons (negative loss factor) that is very difficult to evaluate in its correct magnitude.

In order to discuss the effect of photon loss on a typical O-star atmosphere I have assumed a constant loss factor, $f^* = 10^{-4}$, throughout the whole atmosphere. The justification for the use of this constant will be given below. I have investigated in detail the effect on a model characterized by the stellar

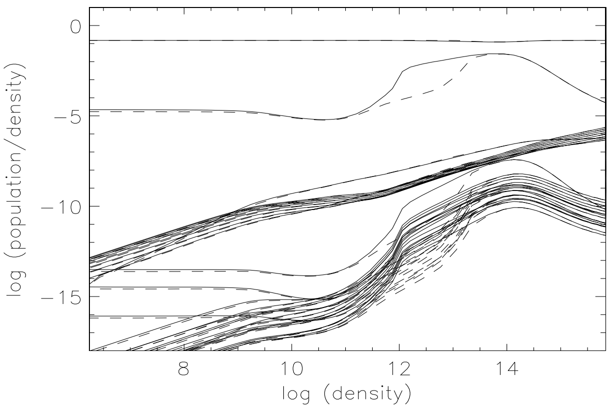

Figure 2. Effect of photon loss from the He II $\lambda 303$ transition on the ionization structure of helium. The model is characterized by $T_* = 40\,$kK and $\dot{M} = 10^{-5.5}\ M_\odot\ \mathrm{yr}^{-1}$ (the other stellar parameters are given in the text). The full-drawn lines denote the level populations of the model including photon loss ($f^* = 10^{-4}$) and the dashed lines indicate the populations without taking into account photon loss. The line around the value -0.8 (ratio of population to density) gives the population of He^{2+}; that between -2 and -5 gives the level population of the ground state of He^+; below that are the excited He^+ states ($n = 2$ behaves somewhat differently); and then the populations of He^0 states are shown.

parameters $T_* = 40\,$kK, $R_* = 20 R_\odot$, $\log g = 3.5$, $X = 0.58$, $Y = 0.41$, $Z = 0.01$, $\dot{M} = 10^{-5.5}\ M_\odot\ \mathrm{yr}^{-1}$, $v_\infty = 2000$ km s^{-1}, and a velocity law with $\beta = 1$. This example is similar to a model for the O supergiant ζ Puppis (Schaerer & Schmutz 1994).

Figure 1 shows the capture factor f^{cap} and the photon-loss factor f^* as a function of the location in the atmosphere. The capture factor is constant within a factor of two, and its value is of the order of $f^{\mathrm{cap}} \simeq 10^{-4}$. This value is very close to that found in a model of a Wolf-Rayet star of type WN5 (see Fig. 16 of Schmutz 1997). The reason for this agreement is given by the fact that f^{cap} is determined mainly by the separation in wavelength of the metal transitions from the helium-line wavelength, and the actual opacities of the metal lines are of less importance (see Schmutz 1997, Eqn. A12). As the ionization conditions are comparable in the O and WN5 atmospheres, the same O III and Fe VI transitions determine the value of the capture factor. Thus the capture factor is expected to be close to 10^{-4} for all atmospheres with similar ionization conditions. As discussed above, as long as there is a *loss* of photons from the line radiation field, $f^* \simeq f^{\mathrm{cap}}$ holds. At $r > 4R_*$ an estimate of the populations of the metal levels yields $S^{\mathrm{m}_i} > \bar{J}^*$ (see Schaerer & Schmutz 1994 for details of the calculation); the second term is larger than the first, and therefore the photon-loss factor is predicted to be negative, i.e., there is a gain of photons for the helium-line radiation field for the outer regions.

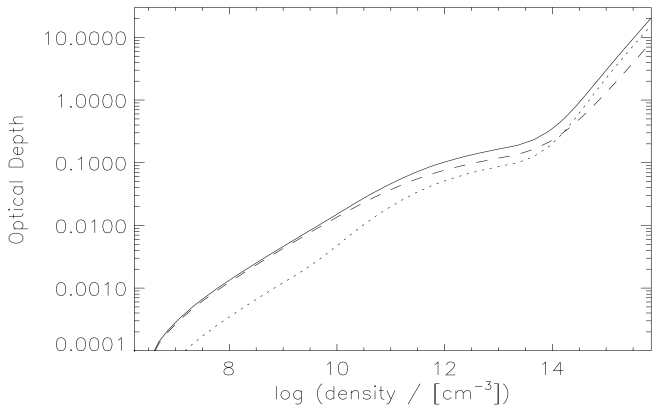

Figure 3. Rosseland optical depth (full-drawn line), Thomson-scattering optical depth (dashed), and thermalization optical depth (dotted) in the same atmosphere model used for Figs. 1 and 2.

In Fig. 2 I illustrate the effect of photon loss on the populations of the helium levels. The model discussed here has an atmosphere where helium is fully ionized, independent of whether photon loss is included or not. As a consequence, the level populations of the excited levels of He^+ are essentially unaffected by photon loss. The ground state of He^+ is directly influenced by the photon loss, but only in a very restricted region of the atmosphere, namely in the range $11 < \log(n) < 13$, where n is the particle density. The populations of He^0 depend on that of the He^+ ground state, and therefore they reflect the dependence of the He^+ ground state on the photon loss. It is a non-trivial result that photon loss influences the populations in only a restricted region, although it was assumed that $f^* = 10^{-4}$ everywhere. This result can be understood by the fact that a small modification of the line radiation field can only affect level populations where the population of the He^+ ground state is determined exclusively by the radiation field in the $\lambda 303$ line. In all other regions there are other rates to and from the ground state, such that a tiny modification of the radiation field can by compensated by a small and unimportant adjustment of the populations. The density range mentioned above, where photon loss modifies the level populations, corresponds to stellar radii $r < 1.4R_*$ ($\log(r/R_*) = 0.15$). A comparison of Figs. 1 and 2 reveals that the sensitive range is well within the region where the photon-loss factor is positive, and close in magnitude to that of the capture factor. As the value of the photon-loss factor does not matter outside the sensitive region, it is unimportant that the assumed constant of 10^{-4} is inconsistent with the calculated value in those regions. It is only important that the photon-loss factor has the correct magnitude where it matters.

Although with Fig. 2 it is demonstrated that photon loss influences the conditions in an O-star atmosphere, this result does not imply that photon loss is important for the spectroscopic analysis of O stars. The relevant question is whether anything happens to the predicted profiles of the lines used as diagnostics. The lines usually used for an analysis of the stellar parameters are

He I λ4471, He II λ4541, He II λ4686, and H I-He II line blends. When inspecting Fig. 2, no changes of the excited He^+ populations can be found, and therefore there cannot be a sensitivity to photon loss of the He II lines. If any line can be expected to react to photon loss, then it has to be He I λ4471 or He I λ5876. However, a comparison of the profiles calculated from models with and without photon loss does not reveal any significant difference for any line in the blue wavelength region, including the He I λ4471 line. There is a slight change of the stronger He I λ5876 profile, but this line is never used to constrain stellar parameters. The insensitivity of He I λ4471 implies that this line is not formed in the region where photon loss modifies the populations. This is confirmed by Fig. 3, where the optical-depth scale is shown. The relatively weak photospheric He I line originates only little above the formation depth of the continuum. From Fig. 3 we learn that the line-formation region is around $\log n \simeq 14$, which is deeper than the region where the level populations are modified by photon loss (Fig. 2).

3. Discussion

The example discussed in the previous section does not prove that photon loss is unimportant for all O-star atmospheres. More models, with other stellar parameters, need to be investigated before we can be certain that photon loss is unimportant for the full range of stellar parameters of O stars. However, I expect that most photospheric lines originate deeper than the region sensitive to photon loss and, in particular, I expect that the lines important for the determination of the spectral type, He I λ4471 and He II λ4541, are among those lines that are not influenced in any O-star atmosphere. Thus, I conclude (provisionally) that photon loss is not important for O stars.

This leaves the effect usually associated with line blanketing: the backwarming of the temperature structure and veiling of the radiation field. These effects have been discussed in great detail by Schaerer & Schmutz (1994) for a model with similar parameters to those discussed above. So far, there is no general overview of the effects of line blanketing on hot stellar atmospheres with stellar winds. I have calculated a grid of models in the range $30\,\mathrm{kK} < T_* < 45\,\mathrm{kK}$ and $-6.5 < \log(\dot{M}/M_\odot\ \mathrm{yr}^{-1}) < -5.0$. The other stellar parameters are the same for all models: $R_* = 20 R_\odot$, $\log g = 3.5$, $X = 0.71$, $Y = 0.28$, $Z = 0.01$, $v_\infty = 2000$ km s^{-1}, and a velocity law with $\beta = 1$. A comparison of Fig. 4 with Fig. 5 illustrates the effect of line blanketing. For a given combination of T_* and $\dot{M}$ a model that includes line blanketing yields a higher degree of ionization, i.e., a smaller ratio of of the equivalent widths of He I λ4471 to He II λ4541. This effect has a clear dependence on the mass loss: stronger stellar winds produce a more pronounced blanketing effect.[1] As the luminosity classes of O stars are strongly correlated with the mass-loss rate, Fig. 5 not only illustrates the dependence of the spectral types on temperature, but also on luminosity class: a

[1]The method used to implement the effects of line blanketing is more reliable for strong stellar winds than for weak mass-loss rates (see Schaerer & Schmutz 1994). The magnitude of this systematic error is not known, but I believe most of the mass-loss dependence of line blanketing illustrated by the comparison of Figs. 4 and 5 is real.

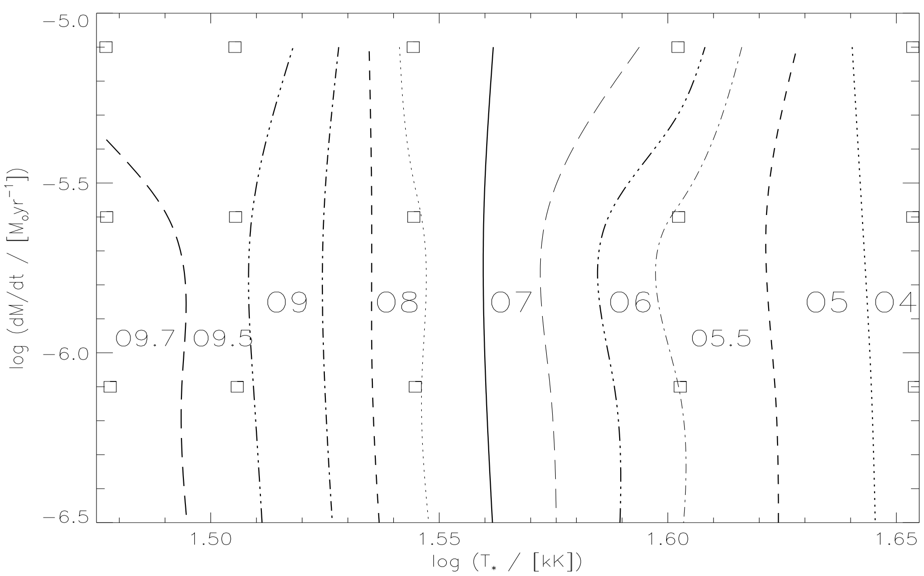

Figure 4. Relation between spectral type and the stellar parameters $T_{\rm eff}$ and $\dot{M}$, based on models *without* line blanketing and photon loss. The lines indicate the location in the T_*–$\dot{M}$ plane of a given value of the ratio of the equivalent widths of He I λ4471 to He II λ4541. The conversion to spectral types is based on Table III of Mathys (1988). The lines are interpolated from the results of the models denoted by squares. All model parameters other than T_* and $\dot{M}$ are identical for all models (see text); in particular, $\log g = 3.5$.

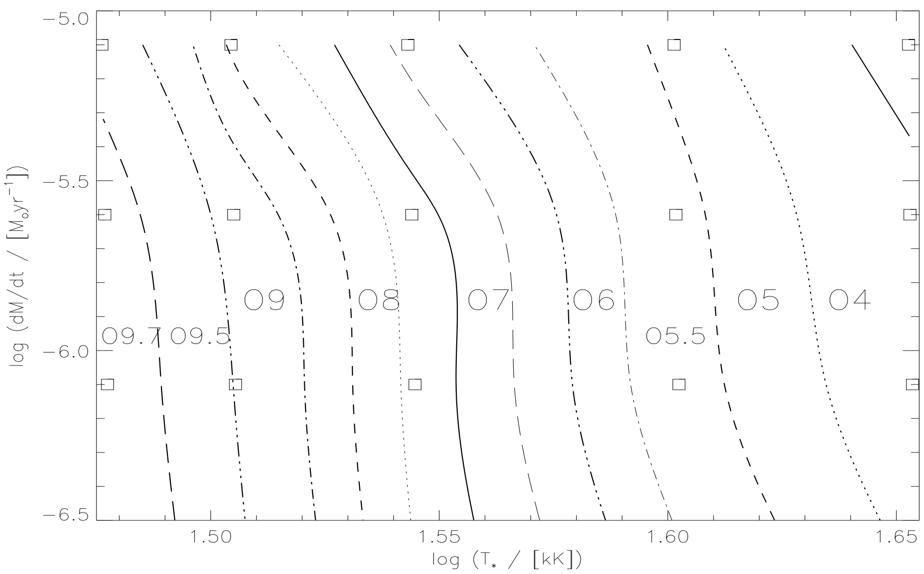

Figure 5. As Fig. 4, but for models *including* line blanketing and photon loss. The models have $Z = 0.01$ by mass, i.e., $Z = 0.5 Z_\odot$.

mass-loss rate of $\dot{M} \simeq 10^{-6}\ M_\odot\ \mathrm{yr}^{-1}$ may be associated with O giants, larger mass-loss rates with supergiants, and smaller ones with main-sequence stars. However, it should be emphasized that the calibration of spectral types in Fig. 5 is based on a constant gravity of $\log g = 3.5$, which is more appropriate for supergiants than main-sequence stars.

Saying that photon loss is unimportant is certainly not a correct statement in general. The above conclusion is meant for spectroscopic analyses; but I would like to emphasize that photon capture certainly *does* occur, and that there are atmospheric regions where photon loss influences the level populations. It is very likely that the strong resonance lines in the UV, such as Si IV λ1400 or C IV λ1550, are sensitive to photon loss from the He II λ303 transition, and maybe even to photon loss from their own radiation field. Another issue which should be investigated in the future for its sensitivity to photon loss is the acceleration of the radiation-driven winds. It could be that the behavior of the velocity law turns out to be sensitive to photon loss.

Acknowledgments. I thank Orsola De Marco for critical comments on the manuscript and Ian Howarth for motivating me to write up my contribution.

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Discussion

Walborn: I'm not sure that I completely understand how you looked at the relationship between spectral type and temperature. You showed a constant T_{eff} for a given spectral type as a function of luminosity?

Schmutz: Let me explain this diagram a little bit more carefully: I plot contour lines of the ratio 4471/4545 [Figs. 4 & 5]. Then I plot what Mathys assigns as borders between spectral types. Of course, there is always a problem in plotting more than two parameters, and here there is also the gravity parameter, and metallicity and so on, so the borders can move around a little bit.

Walborn: In previous calibrations, at a given spectral type there was a decrease in T_{eff} with increasing luminosity, simply because of the gravity dependence of the line ratios.

Schmutz: Sure, that's here too.

Walborn: But you're saying that the reason for that is due to mass-loss rather than gravity?

Schmutz: Yes; well, both are important! But mass-loss rate is *more* important.

Puls: With respect to this photon-loss factor, I studied your paper, and my interpretation of it comes down to the following: what you are doing, in effect, is changing the local escape probability. So really it is no surprise that by putting in the photon-loss factor in thin lines, in O stars, you really get no effect, since the photon-loss factor is much smaller than the escape probability.

Schmutz: Yes, that's basically correct; but the He II λ303 line isn't optically thin in O stars, and in fact there is a region where photon loss does affect the populations. This happens to be outside the region where the standard optical diagnostic lines are formed.

Puls: Okay; but what we really want to do is suppress the source function, and there's another way to do that, namely, not to change the denominator, but to change the numerator – i.e., the incident intensity (normally the irradiation field). Is it not possible that the real effect which is decreasing the source function is not so much the increase of the local escape probability, but the decrease of the incident radiation? That is, that you underestimate line blocking?

Schmutz: This point has also been raised by Leon Lucy, actually. The answer is, for the O stars, that might be an important effect. For the Wolf-Rayet stars, I don't believe it makes a difference, because the helium line is so immensely optically thick that the incident radiation is basically unimportant. Since photon loss has an important effect, even though it's very very small, only around 10^{-4}, that's a clear sign that the line 'feeds' on itself, and only on itself.

Puls: Yes, but it's big with respect to the escape probability, which is 10^{-6}.

Schmutz: But as soon as you have something else influencing the level populations, they will not react to photon loss any more. This is the basic reason why no other lines are affected; they are embedded in a rate scheme that is much more robust. You have to isolate this transition from everything else, otherwise it will not respond to a small photon loss. The rates between $n = 1$ and 2 are so huge that if you do a little bit they don't care – unless the line is isolated. But if the radiation field is generated just by the line, then it's very sensitive to a little disturbance.

Najarro: Werner, you suggest that this photon-loss mechanism is through iron. For the Wolf-Rayets, where photon loss is important, have you been able to correlate this with abundance differences between SMC and Galactic objects?

Schmutz: Actually, for Wolf-Rayets, it's not so much the iron lines as Ca V, but it's not just one line. But it doesn't much matter how strong the line is, just where it is in the helium-line profile. Of course, if you take it away completely, that's important, but as long as there is a line, and it's comparable in opacity with the wings of the He II, then it will work.

Najarro: But the branching ratios will be different; shouldn't you see that in the photon-loss factor?

Schmutz: Not really. Let me put it this way: the photon loss is actually quite complicated, but the *capture* factor is just a question of where the line sits in the wings. Of course, if you take away the line completely, it will not work, so maybe there would be a problem in the SMC; but in the Galaxy and the LMC it will be the same.

Kudritzki: I guess we could have endless discussion about this, but what it really comes down to is that correct treatment of the multiline effects around the resonance line is crucial. I want to draw attention to the fact that this isn't the only resonance line which is important in Wolf-Rayets; the *neutral* helium line at 504Å is also terribly important.

Schmutz: Yes; it depends on the temperature range you're working at.