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Letter to the Editor

A possible solution for the [Ne III] problem in H II regions

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Abstract. By means of realistic model atmospheres for O-type stars, we investigate the influence of EUV radiation on the ionization structure of H II regions. Our model calculations are based on a detailed multilevel NLTE treatment including radiation-driven wind theory and a consistent calculation of NLTE line blocking opacities for all contributing ionization stages. This is especially important since the spectral distribution of our ionizing fluxes is mainly influenced by the two partly compensating processes of (i) metal line blocking and (ii) the effect of a stellar wind. Even very low mass-loss rates affect the subsonic density structure and, consequently, the emergent flux.

By applying our emergent fluxes to a standard nebular code we find, compared to other investigations, an improved match between the observed and calculated ionization structure. In particular, the relatively high ionization fraction of Ne^{++} is well reproduced by our calculations. Thus, our emergent ionizing fluxes provide a solution to the persistent [Ne III] problem in H II regions. In addition, the fractions of O^{++} and S^{++} are changed with the consequence that the relation between the ratio O^{++}/S^{++} and the temperature of the ionizing source is modified.

Key words: H II regions – ultraviolet: stars – stars: atmospheres – stars: early type – stars: mass-loss

1. Introduction

Over the past decade, there has been mounting evidence of a prominent discrepancy when trying to explain the intensities of [Ne III] 36 μm and 3868 Å. The observed line intensities are generally significantly underestimated by photoionization models, in some cases by up to 1.5 dex. This persistent discrepancy has been termed the "[Ne III] problem". Papers that document this problem are Simpson et al. (1986), Rubin et al. (1991), Baldwin et al. (1991), Colgan et al. (1993), Simpson et al. (1995) and Rubin et al. (1995).

A number of possible solutions have been proposed in the past. First of all, it is possible that an overabundance of neon is the cause of the increased emission in the [Ne III] lines. However, this explanation was ruled out by observations of the [Ne II] line at 12.8μm (cf. Rubin et al. 1991). The dominant ionization stage Ne^{+} confirms a normal neon abundance.

Second, the atomic data used for nebular calculations are always an element of uncertainty. Rubin et al. (1995) investigated possible effects of errors in the photoionization cross-sections on the ionization equilibrium of neon. According to their estimates, it is most unlikely that uncertainties in these or other relevant atomic data can explain the large discrepancies between the observed and predicted neon lines.

Furthermore, there is evidence for internal dust in most of the observed H II regions. The dust extinction varies with frequency and therefore changes the spectral distribution of the ionizing flux. Since the cross sections of both silicates and graphites are expected to decrease shortward of ≈ 900Å (c.f. Martin & Rouleau, 1991), this could be the cause of an increased ratio of Ne^{++}/Ne^{+}. However, a simple estimate shows, that a very high amount of internal dust ($\tau_{\rm dust}(1{\rm Ryd}) \gtrsim 100$) is neccessary to explain a discrepancy of an order of magnitude in the population of Ne^{++}. Such an optical depth in the Lyman continuum would decrease the Lyman flux by a factor of 10^{46} and is in contradiction with the observation of ionized hydrogen (c.f. Panagia, 1974).

Finally, the [Ne III] problem may be solved by using more accurate estimates of the ionizing fluxes from the O-stars that are embedded in the nebula. These fluxes are an important input for nebular calculations. They are usually obtained from Kurucz model atmospheres (e.g. Kurucz 1979, 1991), which assume a plane-parallel and hydrostatic photosphere in Local Thermodynamic Equilibrium (LTE). His models include a very detailed treatment of (photospheric) line blocking, which mainly determines the emergent flux between 1 and 4 Rydbergs (i.e., between 912 and 228 Å). However, the adequacy of Kurucz models for nebular calculations is not clear, since the fluxes of early-type stars are characterized by severe departures from LTE and are modified by the onset of a radiation-driven stellar

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Send offprint requests to: Florian H. Sellmaier (florian@usm.uni-muenchen.de) wind (References can be found in the last review by Kudritzki and Hummer, 1990).

Rubin et al. (1995) attempted to overcome part of this problem by adopting improved ionizing fluxes. They used a grid of model atmospheres by Kunze (1994), which include a NLTE treatment for hydrogen, helium and selected metals but still are hydrostatic and plane-parallel. With these models, the Ne^{++} fractional ionizations in the nebular models were significantly increased, and indeed diminished the [Ne III] problem. However, this success is not convincing, since Kunze's model atmospheres do not consider the line blocking due to the Fe group elements, which produce the largest contribution to the blocking opacities shortward of 912 Å (cf. Haas et al. 1995; Pauldrach et al. 1994a).

In this work, we concentrate on the calculation and use of realistic ionizing fluxes. We briefly introduce our stellar atmosphere models in section 2 and compare them with the previously used models of Kurucz (1991) and Kunze (1994). In section 3 we use these fluxes as input for a nebular photoionization calculation and discuss the consequences for the ionization structure of H II regions.

2. Realistic stellar atmosphere models for O stars

The combined spectrum of the ionizing sources in an H II region is dominated by the spectrum of the hottest and brightest star. This is in general an O star with an atmosphere influenced by NLTE effects, spherical extension and a stellar wind. Additionally, the computation of the ionizing flux between 1 and 4 Rydbergs requires an adequate treatment of metal line blocking in NLTE.

A new generation of stellar atmosphere models which fulfill these requirements was recently developed by Sellmaier & Pauldrach (1995) and Pauldrach et al. (1994b). The major advantage of these models is the consistent calculation of blocking opacities in NLTE based on more than 2.5 million lines and 149 ionization stages. NLTE occupation numbers are calculated for essentially all contributing ions including the iron group elements. Furthermore, the spherical extension of the atmosphere and the presence of a radiation-driven wind (which is a function of the effective temperature $T_{\rm eff}$, the gravity $\log g$ and the metallicity z) is considered along with its amplifying effect on the metal line blocking due to the lineshift in the wind (cf. Sellmaier & Pauldrach 1995).

First of all, we compare the emergent fluxes of these models with the fluxes of Kurucz (LTE, hydrostatic, photospheric line blocking in LTE) and Kunze (NLTE, hydrostatic, no Fe-group line blocking). The lower panel of figure (1) shows that the emergent flux of Kunze's models at $T_{\rm eff}$ = 40 000 K (dotted line) is overestimated by orders of magnitude compared to our model (solid line) which is decreased in this range mainly due to the line blocking by Fe IV and Fe V. The flux of our models is even below the Kurucz-flux in most parts of the ionizing spectrum. This is a NLTE effect which produces deeper cores of the blocking lines compared to LTE. Such a low value of the ionizing flux is also confirmed by the observed ionization structure in the wind of hot stars (cf. Pauldrach et al. 1994b and Sellmaier & Pauldrach 1995). In other words, a higher value of the emergent flux would be in contradiction with the observed strength of UV metal lines.

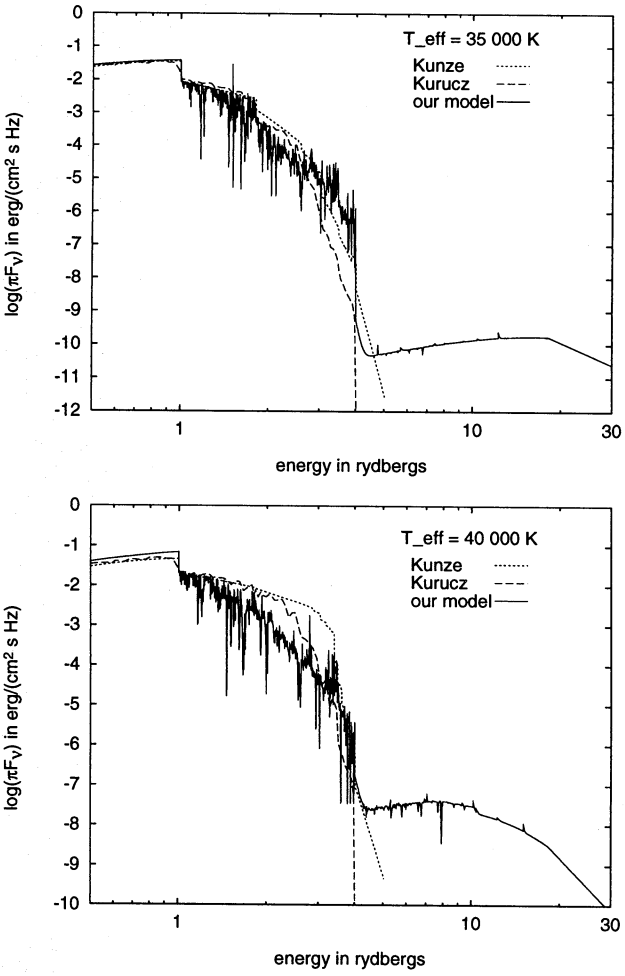

Fig. 1. Comparison of the emergent fluxes calculated with the stellar model atmospheres codes of Kurucz (1992), Kunze (1994) and Sellmaier & Pauldrach (1995) for two different temperatures (Upper panel: $T_{\rm eff}$ = 35 000K, lower panel: 40 000 K)

Regarding the gradient of the flux instead of its absolute value, one can see that our models produce a much flatter flux distribution compared to the result of the plane-parallel and hydrostatic models by Kurucz and Kunze (Fig.1, both panels). This is a consequence of the onset of a stellar wind which both raises the EUV continuum (Najarro et al. 1995; Gabler et al. 1992) and fills up the photospheric absorption lines (Sellmaier et al. 1993). In section 3 we will show that this has important consequences for the diagnosis of nebular emission lines.

Emergent fluxes for selected O-stars

The approach of this work is to compute realistic atmospheres for a few representative O-stars with observed optical spectra and X-ray luminosities instead of calculating an extended grid of models. Thus we have good constraints on the structure

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of the atmosphere and the ionizing flux due to their observed influence on other parts of the spectrum. We selected the three O-stars ξ Per, HD217086, and HD93129A (classified as O7.5III, O7V, and O3I respectively) to construct models with similar parameters (Table 1). They were observed and analyzed by Puls et al. (1995) and Chlebowski et al. (1989).

Table 1. Stellar parameters for our models

$T_{\rm eff}$ [K]	35000	40000	50000
$\log g$	3.5	3.8	3.9
$R_*[R_\odot]$	25	10	20
$z[z_\odot]$	1	1	1
$\dot{M}$ $[10^{-6}M_\odot/yr]$	1.9	0.8	9.9
v_∞ [km/s]	1786	1725	2167
$\log L_X/L_{\rm Bol}$	- 6.60	- 6.62	- 6.36

The parameter which mainly determines the shape of the ionizing flux is $T_{\rm eff}$ whereas the other parameters $\log g$ and R_* play a subordinate role. The wind parameters $\dot{M}$ and v_∞ are actually a result of our calculations. We simulated also the X-ray emission due to shocks (Fig. 1, bump beyond 4 Rydbergs. For the method: see Pauldrach et al. 1994b), to check possible effects of the emergent flux beyond the He II edge on the ionization in the nebula.

3. Calculation of the ionization structure in H II regions

The emergent fluxes of our models are used as an input for nebular calculations with the photoionization code CLOUDY (version 84.06) of Ferland (1993). The other input parameters are adopted from the "standard nebular model" of Rubin et al. (1995). The total density is 10^3 cm^{-3}, the number of hydrogen ionizing photons, $Q({\rm H}) = 10^{49.5}\,{\rm s}^{-1}$, and the chemical composition is that of the Orion Nebula (Normalized to Hydrogen the abundances are He: 0.1, C: $2.8\cdot10^{-4}$, N: $6.8\cdot10^{-5}$, O: $4.0\cdot10^{-4}$, Ne: $8.1\cdot10^{-5}$, Si: $4.5\cdot10^{-6}$, S: $8.5\cdot10^{-6}$, Ar: $4.5\cdot10^{-6}$, Fe: $3.0\cdot10^{-6}$). The assumed inner radius of the nebula is the stellar radius and the the outer radius is defined by the position where $T_{\rm e} < 4\,000$ K.

Figure 2 shows the results in the $<{\rm Ne}^{++}>$Ne/$<{\rm O}^{++}>$O vs. $<{\rm O}^{++}>$O/$<{\rm S}^{++}>$S plane (the definition of the avaraged ionization fractions $<{\rm X}^{++}>$ can be found in Rubin et al., 1994). We find excellent agreement between the result of our emergent fluxes (large open triangles) and the points that are derived from the [Ne III] 36 μm observations (filled circles). This agreement is dramatic when compared to the results using Kurucz's fluxes (large open circles) or even using Kunze's fluxes (large open squares) which correspond to the results published in Rubin et al. (1995).

Note that Kurucz's and Kunze's models correspond to main sequence stars (with $\log g$ ranging from 4.0 to 4.2 for $T_{\rm eff} \leq$ 40 kK, 4.3 for 43 kK, and 4.6 for 50 kK) whereas we have modeled a giant, a main sequence star and a supergiant (with $\log g$ given in Table 1). However, when a realistic stellar wind is present we find that gravity has almost no influence on the gradient of the emergent flux and hence on the positions in Fig. 2.

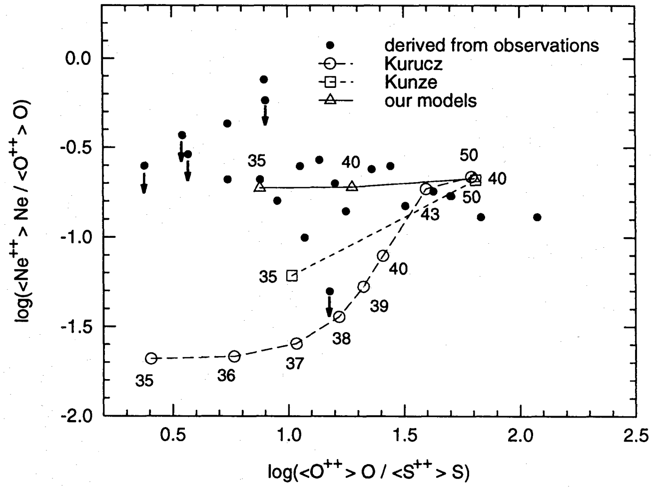

Fig. 2. Diagnostic diagram, which demonstrates the [Ne III] problem. The filled circles are derived from observations by Simpson et al. (1995). The large open symbols are results of the same photoionization code (CLOUDY 84.06) but different ionizing fluxes. For further details see text.

The reason for the increased fraction of Ne^{++} in the nebula can be seen in Fig. 3 where the ionizing flux of all models has been scaled[1] such that the number of hydrogen ionizing photons Q(H) is constant. The flatter gradient in the flux of our models is responsible for an increased population of Ne^{++} compared to O^{++} and S^{++} and hence the explanation for the [Ne III] problem.

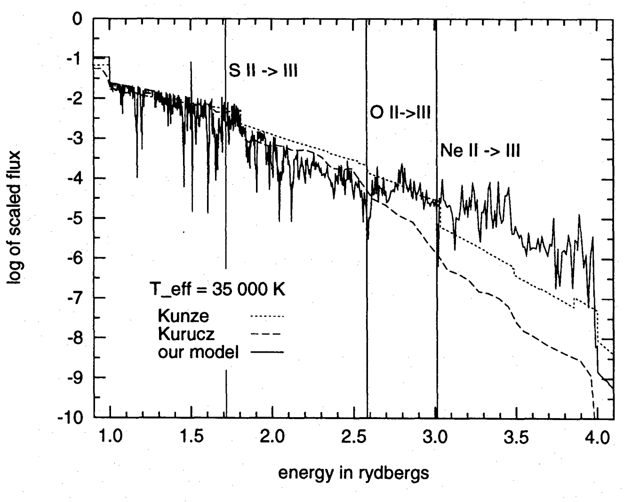

Fig. 3. Ionizing flux from the 35 000K models shown in Fig. 1 normalized to the same number of Lyman photons. The vertical lines indicate the ionization edges for S II, O II and Ne II

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[1] Since the number (and the radius) of the ionizing sources is unknown the emergent fluxes of the stellar atmosphere models are scaled to the "observed" number of hydrogen ionizing photons. Thus, the scaling factor represents the number of O-stars embedded.

It is obvious that not only the population of Ne^{++} is changed but also that of other ions, especially the ratio O^{++}/S^{++} which is used as an indicator for the temperature of the ionizing star(s) (see Fig.2). However, most of the other ions used in standard diagnostics are much less affected since their threshold energies are lower and the ionizing fluxes below 2.7 Rydberg do not differ that much from the Kurucz models (c.f. Fig.3).

In addition we tested the influence of shock-produced radiation beyond the He II edge by switching off the stellar flux for energies greater than 4 Rydbergs: No differences were found for the investigated ionization fractions in the nebula.

4. Conclusions

We applied our new stellar atmophere models to nebular theory and found the following results:

1. A plausible explanation for the high intensities of [Ne III] 36 μm and 3868 Å emitted from H II regions is provided. No alternative mechanism is neccessary to explain the magnitude of the "observed" Ne^{++}. The scatter of the points in Fig.2 might be caused by (i) different luminosity classes of the ionizing source(s), (ii) variations in the geometry or density of the nebula, (iii) effects of inhomogeneity, or (iv) changes in the amount and distribution of internal dust.
2. Other ionization fractions are also affected. Specifically, this changes the relation between the temperature of the ionizing source(s) and the ratio of S^{++}/O^{++}.
3. The number (or the radius) of the ionizing sources is higher than previously thought. The scaling factor between the emergent flux of the stellar atmosphere models and the number of photons Q(H) which ionize the nebula is 1.5 times higher for our 35 kK model than for the Kurucz model and 1.7 times higher compared to Kunze.
4. The shock emission beyond 4 Rydbergs does not influence the investigated ionization fractions in the nebula (Ne^{++}, O^{++}, S^{++}).

The results 1., 2., and 3. are a product of the two counterbalancing processes of NLTE line blocking and the onset of a stellar wind which were not treated in previously used models. The first effect primarily decreases the absolute value of the emergent flux whereas the second effect predominantly changes its gradient. We will publish a detailed explanation of these effects in a subsequent paper together with the ionizing fluxes of an extended grid of model atmospheres.

Since the emergent fluxes of almost all O-type stars – from the main sequence to supergiants – are influenced by both NLTE line blocking and a stellar wind, future work in nebular theory should use model atmospheres which account for these processes. This is also true for other fields, whenever a composite spectrum of early type stars is relevant, e.g., in research on starburst galaxies.

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