Non-LTE Line-Blanketed Model Atmospheres of O Stars

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Abstract. A brief review of the recent progress in model atmospheres for hot stars is presented. We show that, since departures from LTE as well as the effects of metal-line blanketing are very important, one has to construct fully blanketed non-LTE model atmospheres for these objects. We show that the recent progress in the fast numerical methods, namely those based on the Accelerated Lambda Iteration, has led to an enormous progress in the degree of realism in computed model atmospheres. The importance and the power of the new model atmospheres is illustrated on an analysis of HST/GHRS observations of the main-sequence O9 V star 10 Lac.

1. Introduction

Model atmospheres which take into account simultaneously departures from local thermodynamic equilibrium (LTE) together with the effects of millions of metal lines – metal-line blanketing – are called non-LTE line-blanketed models. In the last decade, there has been a considerable effort by several research groups to compute such model atmospheres and to study the effects of non-LTE line blanketing on the atmospheric structure and predicted stellar spectrum.

The pioneer of the field is Lawrence Anderson, who more than a decade ago set forth to go boldly where no-one had gone before, and developed a numerical scheme, called the 'multi-frequency/multi-grey algorithm' (Anderson 1985), which enabled him to construct models with hundreds to thousands of spectral lines in non-LTE. The next crucial point was the development of a whole class of approaches, generically referred to as Accelerated Lambda Iteration (ALI) methods (for a review, see, e.g., Hubeny 1992). The ALI formalism was first applied for constructing model stellar atmospheres by Werner (1986, 1989), and later upgraded to metal-line-blanketed models by Dreizler & Werner (1993).

Our group has developed a robust numerical scheme, called the hybrid complete linearization/accelerated lambda iteration method (Hubeny & Lanz 1995), and applied it to constructing non-LTE line-blanketed model atmospheres for hot, metal-rich DA white dwarfs (Lanz & Hubeny 1995; Lanz et al. 1996b), O stars (Lanz et al. 1996a), and hot sdO subdwarfs (Lanz, Hubeny & Heap 1997).

In this paper we will discuss non-LTE metal-line-blanketed model atmospheres of O-type stars. Since the O stars are very important objects in the general astrophysical context, their reliable spectroscopic diagnostics are of utmost importance for many branches of astrophysics. Luminous O stars are known to possess stellar winds. Consequently, realistic model atmospheres should, in principle, describe all layers starting from the essentially hydrostatic *photosphere* up to highly dynamic winds on the same footing. Such models are called *unified model atmospheres,* and their computation was pioneered by the Munich group (Gabler et al. 1989; Sellmaier et al. 1993; Pauldrach et al. 1998). The problem is very complex; it is understandably necessary to make a number of simplifying approximations.

Our philosophy is as follows. While it is extremely difficult to construct 'exact' unified model atmospheres, the present developments in computer speed and memory, together with advances in fast and reliable numerical methods, make it possible to construct extremely sophisticated – practically exact – model photospheres, i.e., the atmospheric layers where the traditional assumptions of plane-parallel stratification and hydrostatic and radiative equilibrium hold. We are now able to take into account departures from LTE for a large number of energy levels of all important chemical species that determine the atmospheric structure, such as H, He, C, N, O, Si, Fe, and Ni.

Why do we construct such models? First, we may study the differences between the previous simple models and the new ones, with the aim of evaluating the differences in the deduced basic stellar parameters when these models are used in interpreting an observed stellar spectrum. Secondly, for all but extremely large values of the mass-loss rate, most of the observed spectral features are actually formed in the photosphere, so that the photospheric models can be used in many cases to deduce basic stellar parameters, such as the effective temperature, surface gravity, and chemical composition. Finally, from the methodological point of view, one has to proceed step by step. One has to understand well the effect of non-LTE metal-line blanketing on the atmospheric structure (temperature, ionization stratification, etc.) in a simpler hydrostatic case before one can hope to achieve full understanding of the more complex structure of winds. In particular, the current unified models use a number of simplifications when computing ionization stratification of chemical species; yet an accurate knowledge of ionization stratification is critical to determining the radiation force which drives the wind.

2. Method

Although the ALI-based methods have opened the way to attack the problem of non-LTE line blanketing, the enormous complexity of the iron-peak elements (i.e., we have to account for hundreds of energy levels and millions of line transitions per ion) still precludes using direct methods that were successfully used for light elements (H, He, C, N, O, Si, etc.).

Statistical methods are therefore necessary. The idea is to avoid dealing with all individual energy levels of complicated metal species. Instead, several states with close enough energies are grouped together to form a so-called 'superlevel.' The basic assumption is that all individual levels within the same superlevel share the same non-LTE departure coefficient; in other words, the individual levels forming a superlevel are in Boltzmann equilibrium with each other. This idea was pioneered by Anderson (1989). The transitions between individual superlevels, called 'superlines,' are treated by means of two possible approaches:

- *Opacity Distribution Functions* (ODFs). The idea is to resample a complicated frequency dependence of the superline cross-section to form a monotonic function of frequency; this function is then represented by a small number of frequency quadrature points (Anderson 1989; Hubeny & Lanz 1995).

- *Opacity Sampling* (OS). The idea is a simple Monte-Carlo-like sampling of frequency points of the superlevel cross-section (Anderson 1991; Dreizler & Werner 1993). The advantage of this approach is that it can easily treat line blends and overlaps; the disadvantage is that one has to be very careful to choose a sufficiently large number of frequency points, since otherwise the representation may be inaccurate. Indeed, the line cores, which represent the region of maximum opacity, are relatively narrow. Considering too few frequency points may easily lead to missing many important line cores.

These two approaches are illustrated in Fig. 1. We consider the superline between the superlevels 1 and 13 of the Hubeny & Lanz (1995) model of Fe III. The detailed cross-section (upper panel) has been computed for some 16 000 internal frequency points. The dotted line in the middle panel represents the Opacity Sampling by 37 (equidistant) wavelength points, while the number of points is doubled for the full line. This shows that unless a large number of frequency points is considered, the OS representation may be quite inaccurate, since practically all strong lines are missed. Finally, the lower panel shows the Opacity Distribution Function representation. With 24 points only, we have already a fairly accurate representation of the resampled cross-section to be used in model-atmosphere construction.

The strategy for computing line-blanketed model atmospheres is as follows. Hydrogen, helium, and the most important light metals (C, N, O, possibly others) are represented by detailed atomic models, and all the individual lines are treated separately. This involves of the order of 200 atomic levels, and up to 1000 lines, which are represented by several thousand frequency points. The heavy (iron-peak) metals are treated by means of the statistical, ODF or OS, approach. Since the dominant opacity is provided by iron and nickel, we either neglect all the other iron-peak elements, or group all of them together to form an averaged iron-peak element (as suggested first by Anderson 1989).

3. Results

3.1. Sensitivity Analysis

Figure 2 shows the temperature as a function of depth (expressed, as usual, as column mass in g cm^{-2}) for representative model parameters: $T_{\rm eff} = 35\,000$ K and $\log g = 4$. We consider several non-LTE model atmospheres: (*i*) a H/He

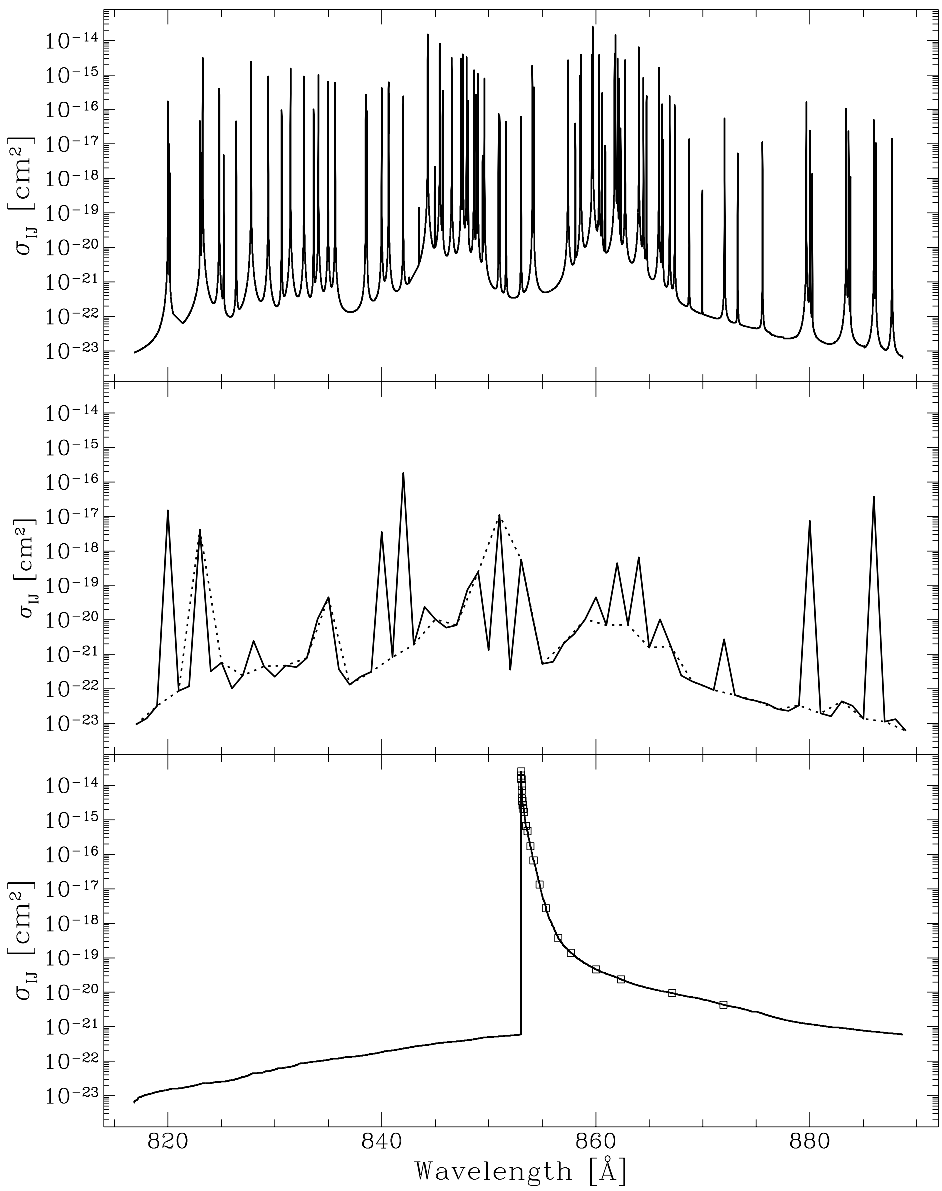

Figure 1. An illustration of various numerical treatments of a typical superline. Upper panel: the detailed cross-section; middle panel: the Opacity Sampling representation; lower panel: the Opacity Distribution Function representation. Small squares indicate the points used to represent this ODF in the model atmosphere calculations.

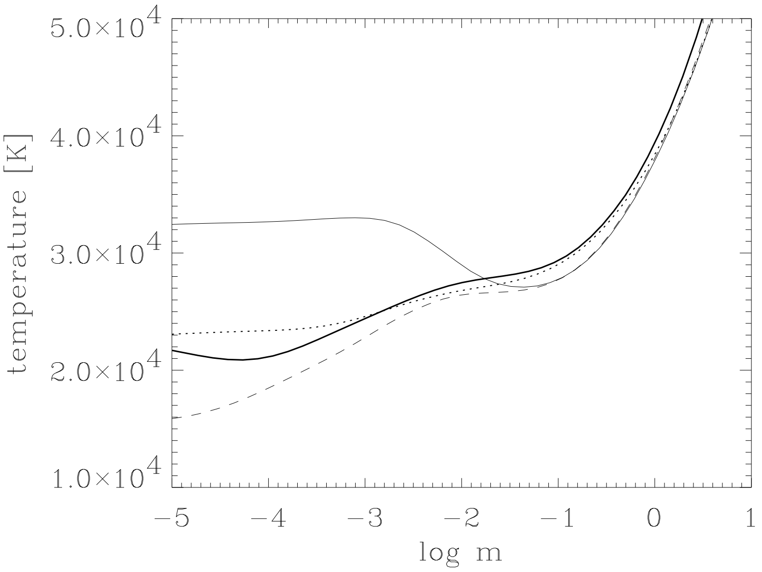

Figure 2. Temperature structure for four model atmospheres with the same parameters: $T_{\rm eff} = 35\,000\,{\rm K}$ and $\log g = 4$. Thick line: fully blanketed non-LTE H/He-CNO-Si-Fe-Ni model; dashed line: non-LTE model with light elements (H/He-CNO-Si); thin line: non-LTE H/He model; dotted line: LTE H/He model.

model; (*ii*) a H/He-CNO-Si-Fe model; and (*iii*) a H/He-CNO-Si-Fe-Ni model. All models are non-LTE/L models, i.e., they consider all lines originating between explicit levels of all species that are taken in account. The models were constructed using our code TLUSTY (Hubeny 1988; Hubeny & Lanz 1992, 1995).

The H/He non-LTE model exhibits a significant temperature rise in the upper layers ($\log m < -2$), discovered by Auer & Mihalas (1969), and explained as an indirect effect of hydrogen lines on the heating due to the Balmer and Lyman continuum. Including lines of CNO, in particular the C IV resonance lines, causes a dramatic cooling for $\log m < -1.5$. This effect was first demonstrated numerically by Anderson (1985). Iron lines cause the well-known backwarming effect (in the layers at $\log m \simeq -1$). However, unlike the traditional view, the iron lines do not cause additional surface cooling with respect to the H/He-CNO-Si model. This is because the presence of iron lines leads to changes in the ionization balance of light metals, as well as hydrogen and helium, which in turn leads to a decreased surface cooling due to H, He, and CNO lines. We stress that the behavior of the temperature at the surface has only academic significance. It does not influence any observed spectral features except the very cores of the strongest lines (e.g., the C IV resonance lines), but these features are in reality influenced by a stellar wind, which is neglected in present hydrostatic models anyway. Therefore, the most important effect of line blanketing is its influence on temperature for layers with $\log m$ larger than, say, -3.

More interesting is the effect of non-LTE line blanketing on the predicted UV spectrum. The effect is best shown if we form a ratio of the predicted spectrum for given model with respect to the spectrum for the H/He-CNO-Si-

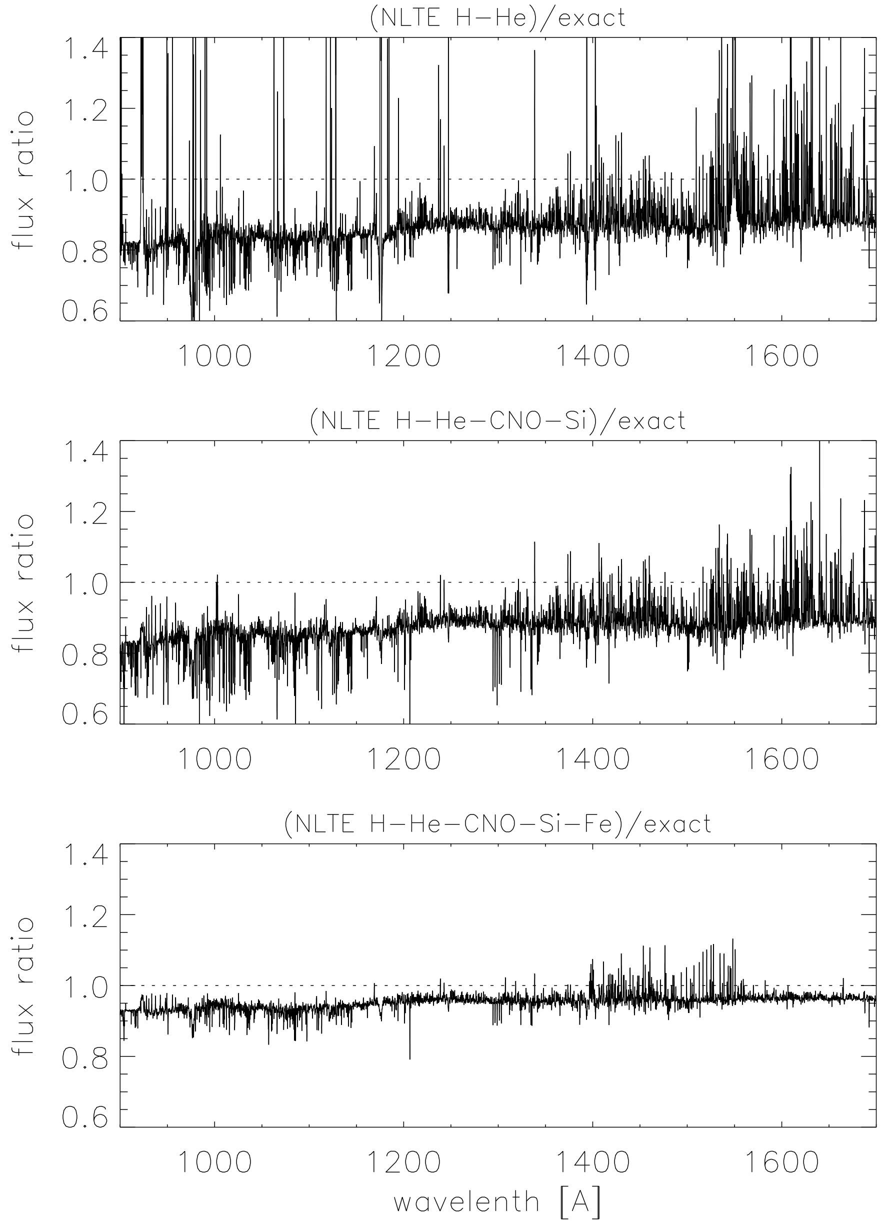

Figure 3. Ratio of the emergent flux predicted for various simplified model atmospheres to the flux predicted by the 'exact' model, i.e., a fully blanketed non-LTE model; see Section 3.1 for details. The flux is convolved with instrumental broadening with FWHM = 0.2Å.

Fe-Ni model, which we call the 'exact' model. We compute the spectra using the code SYNSPEC (Hubeny, Lanz & Jeffery 1994). In this code, all lines between levels that were treated in non-LTE in an input model are computed with an non-LTE source function by SYNSPEC; the remaining lines are assumed to be formed with an LTE – Planckian – source function. Figure 3 shows these flux ratios. We stress that in all models we always consider all lines of all species, taken from the Kurucz (1994) line list; the only differences in the predicted spectra are due to different atmospheric structure and/or different treatment of lines (LTE or non-LTE), and not because some lines are missing (in such a case the differences in the predicted spectra would have been much larger).

The upper panel of Fig. 3 displays the ratio for the non-LTE H/He model; i.e., the atmospheric structure is computed assuming non-LTE for H and He, but the metal lines are computed assuming LTE. The comparison shows that the UV flux tends to be systematically lower for the H/He model, which follows from the lower temperature for the latter model because of the neglection of backwarming. The difference is typically 20%. On top of that, there are significant differences in line profiles, which go both ways – i.e., the H/He model produces either lower or higher flux in the individual lines, depending on details of non-LTE formation of a particular line in question.

The middle panel shows an analogous ratio for the H/He-CNO-Si model. Since the temperature structure in the continuum-forming layers (i.e., around $\log m \simeq -1$) is very similar to the H/He model, the systematic difference in the continuum is about the same as that displayed in the upper panel for the H/He model. This shows that by computing H/He-CNO-Si non-LTE models one does not gain much improvement in the predicted UV continuum flux. An improvement is achieved in predicted profiles for CNO and Si lines (many significant peaks in the flux ratio indeed disappeared for the H/He-CNO-Si model). The remaining 'noise' in the middle panel is thus caused by the non-LTE effects in Fe and Ni.

Finally, the lower panel shows the ratio of the model blanketed by only Fe to the exact one. The systematic difference on the continuum level is now much lower, yet still visible: about 5%. This clearly shows the importance of Ni on model atmospheres of O stars, and also the importance of non-LTE effects for Ni.

3.2. Application to HST/GHRS Observations of 10 Lac

To illustrate the overall quality of our non-LTE line-blanketed models, we present a sample of the observed UV flux of 10 Lacertae (O9 V), taken by GHRS aboard HST, together with predictions of our non-LTE line-blanketed model with $T_{\rm eff} = 35\,000\,{\rm K}$ and $\log g = 4$ (see Fig. 4). The rotational velocity is taken as $v_{\rm e} \sin i = 25$ km s^{-1}. The complete spectrum will be presented elsewhere (Hubeny, Heap & Lanz, in preparation). Here we show only a small part of the UV spectrum, which is typical for the quality of the fit in the whole observed region. We see that the agreement of the observed and the predicted spectra is excellent, which gives us confidence that the non-LTE modelling techniques and the quality of atomic data are sufficiently high to enable us to make truly detailed spectroscopic studies of hot stars.

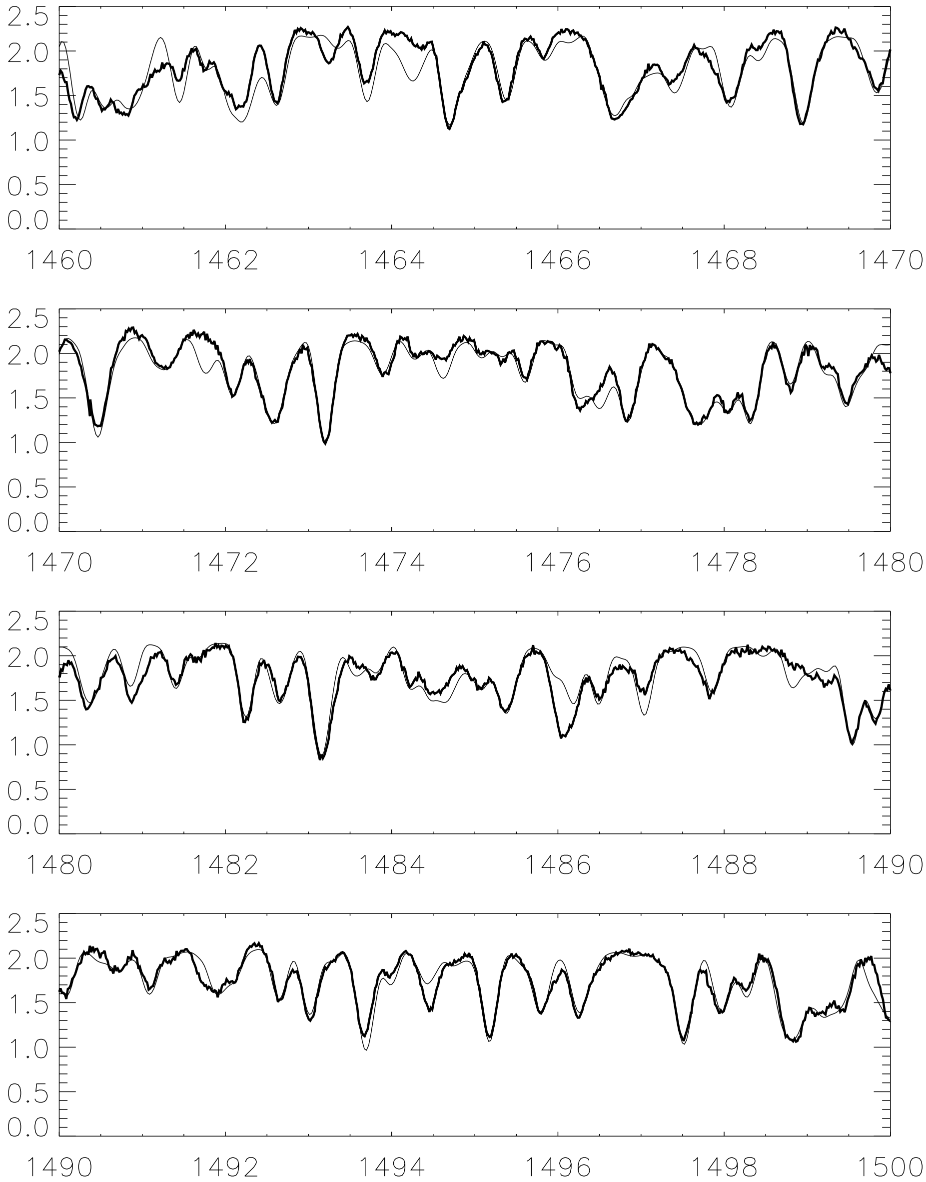

Figure 4. A comparison of the observed HST/GHRS flux for 10 Lac (heavy line) and the predicted flux from the fully blanketed non-LTE model atmosphere with $T_{\rm eff} = 35\,000\,{\rm K}$, $\log g = 4$, and $v_{\rm e} \sin i = 25$ km s^{-1}. The predicted flux is convolved with instrumental broadening with FWHM = 0.06Å. The abscissa is the wavelength in Å, and the ordinate is the flux in 10^{-9} erg cm^{-2} s^{-1} Å^{-1}.

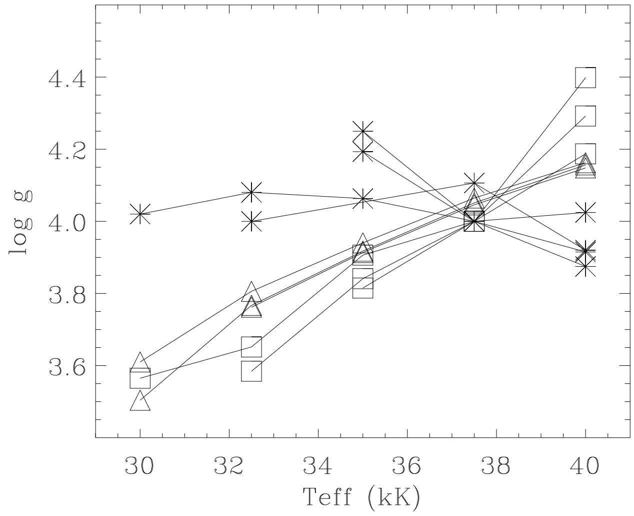

Figure 5. A fit diagram for fitting the H, He I, He II line profiles by means of non-LTE H/He model atmospheres. The 'observed' spectrum is in fact a synthetic spectrum computed for a fully metal-line-blanketed, non-LTE model for $T_{\rm eff} = 35\,000$ K and $\log g = 4$. Squares: hydrogen lines (Hβ to Hδ); triangles: He I lines ($\lambda\lambda$4388, 4471, 4922Å); stars: He II lines ($\lambda\lambda$4026, 4200, 4542, 4686Å).

3.3. Spectrum Fitting Using H and He Lines

Finally, we will illustrate an important point, namely the error one makes if the spectrum is fitted by simple H/He model atmospheres instead of by line-blanketed models. Analogously to the work of Herrero et al. (1992), we will use the method of fit diagrams, which consists of constructing a grid of H/He non-LTE models for a number of values of $T_{\rm eff}$ and $\log g$, and finding the best fit of the individual observed line profiles. The fitting is done by keeping $T_{\rm eff}$ fixed, and finding a value of $\log g$ that fits the observed profile best. One then goes to the next grid value of $T_{\rm eff}$, and repeats the fitting. Every fitted spectral line then defines a curve in the $T_{\rm eff}$–$\log g$ plane, which locates the best-fit values of $T_{\rm eff}$ and $\log g$.

We have constructed a grid of non-LTE H/He model atmospheres with effective temperatures between 25 000 and 45 000 K, at steps of 2500 K, and for $\log g$ between 3.5 to 4.5, at steps of 0.25. All models have the solar abundance for helium. We do not fit an actual observed spectrum; instead, we pretend that the 'observed' spectrum is the synthetic spectrum computed for a fully metal-line-blanketed non-LTE model for $T_{\rm eff} = 35\,000$ K and $\log g = 4$. The fit diagram for H, He I, and He II lines is shown in Fig. 5. A very interesting result is that the H/He models would determine the best fit parameters $T_{\rm eff} \simeq 37\,500$ K and $\log g \simeq 4$. In other words, the H/He models will *overestimate* the deduced effective temperature, which is not surprising in view of the discussion presented earlier, namely that the local temperature in the H/He models in regions where H and He lines are formed is lower than in the line-blanketed models.

4. Conclusions

We have shown that the recent progress in the fast and ingenious numerical methods, namely those based on the Accelerated Lambda Iteration, has led to an enormous progress in the degree of realism in computed model atmospheres. We are now able to compute fully blanketed non-LTE model atmospheres, taking into account literally tens of millions of spectrum lines in non-LTE. What was still a dream at the time of the first Boulder-Munich Workshop is now becoming a reality.

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Discussion

Herrero: Did you find anything out about the helium-abundance determinations?

Hubeny: Well, my purpose wasn't really to do a specific analysis, just to show what errors you make using different methods. So I used solar helium, actually; and you can see, this gives a nearly perfect intersection [Fig. 5].

Walborn: Just an incidental comment about the parallaxes: I've seen a preprint by Henny Lamers which says that, according to HIPPARCOS, 10 Lac has an M_V of -3 [Lamers et al., A&A, 325, L25, 1997]. From the cluster distance you'd assume -4.3, and that's an anchor point in the absolute-magnitude calibration for O9 V, so... I hope the HIPPARCOS results are wrong! [Laughter.]

Kudritzki [to Walborn]: The paper says that the absolute magnitudes of O-type stars as a function of spectral type are correlated with rotation, in the sense that the slow rotators are always much fainter than the fast rotators. One could study that independently of HIPPARCOS if you just looked at clusters.

Harries: You're saying that the inclusion of line blanketing reduces the inferred temperature by 2000 K in the example you've discussed? How would that vary with spectral type?

Hubeny: Well, for hotter stars it will be more, but it's always more or less around 10%. For BD+75° 325 it was 6000 out of 58 000 K.

Puls: If you were to play the same game with your reduced (smaller) Fe and Ni atoms, what would be the effect? Would it take you more or less than half-way to this 2000 K change in the inferred temperature?

Hubeny: Well, in this case it is less than half-way.