Non-LTE Line-Blanketed Model Atmospheres of Hot Stars

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Abstract. A brief review of the recent developments in model atmospheres for hot stars is presented. We show that a significant progress in the fast numerical methods, and in producing new atomic data has led to an enormous improvement of the degree of realism in computed model atmospheres and predicted stellar spectra. 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 NLTE line-blanketed models. In the last decade, there has been a considerable effort of several research groups to compute such model atmospheres and to study the effects of NLTE line blanketing upon the atmospheric structure and predicted stellar spectrum. The crucial point was the development of a whole class of methods, generically referred to as Accelerated Lambda Iteration (ALI – 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 NLTE line-blanketed model atmospheres for hot, metal-rich DA white dwarfs (Lanz & Hubeny 1995; Lanz et al. 1996b), O stars (Lanz et al. 1996a), B giants (Hubeny & Lanz 1996), and to hot sdO subdwarfs (Lanz, Hubeny, & Heap 1997).

Why do we construct such models? First, we may study the differences between the previous simpler models and the new ones, with the aim to evaluate the differences in deduced basic stellar parameters when these models are used in interpreting observed stellar spectra. Second, from the methodological point of view, one has to proceed step by step. One has to understand well the effect of NLTE 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 stellar atmospheres (winds, chromospheres, etc.), or related objects, like accretion disks.
2. Method

Although the ALI-based methods have opened the way to attack the problem of NLTE 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 NLTE 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 the Opacity Distribution Functions (ODF) approach. The basis of this approach 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 and Lanz 1995).

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 1,000 lines, which are represented by several thousands of frequency points. The heavy (iron-peak) metals are treated by means of the statistical (ODF) 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. Application to HST/GHRS observations of 10 Lac

To illustrate the overall quality of our NLTE 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 NLTE line-blanketed model with $T_{\text{eff}} = 35,000$ K and $\log g = 4$ (see Fig. 1). The rotational velocity is taken as $v \sin i = 25$ km/s. About 9.5 millions of lines of 26 ions of H, He, C, N, O, Si, Fe, and Ni are taken into account in model construction. We assume solar abundances for all elements. The model atmosphere were calculated by program TLUSTY (Hubeny 1988; Hubeny and Lanz 1992, 1995), and the detailed spectra by program SYNSPEC (Hubeny, Lanz, Jefferry 1994).

The complete spectrum will be presented elsewhere (Hubeny, Heap, & Lanz, in prep.). 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 spectrum is excellent, which gives us confidence that the non-LTE modeling techniques and the quality of atomic data are sufficiently high to enable us truly detailed spectroscopic studies of hot stars.
Figure 1. A comparison of the observed HST/GHRS flux for 10 Lac (heavy line) and the predicted flux from the fully blanketed NLTE model atmosphere with $T_{\text{eff}} = 35,000$ K, $\log g = 4$, and $v \sin i = 25$ km/s. The predicted flux is convolved with instrumental broadening with FWHM = 0.06 Å. The abscissa is the wavelength in Å, and the ordinate is the flux in $10^{-9}$ erg cm$^{-2}$ s$^{-1}$ Å$^{-1}$.
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 spectral lines in NLTE. What was a dream only a decade ago is now becoming a reality.

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References

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