8. STELLAR ATMOSPHERES

NON-LTE LINE BLANKETED ATMOSPHERES FOR HOT STARS

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Abstract.

The modeling of hot star atmospheres falls into two broad classes: those where the plane parallel approximation can be used, and those where the effects of spherical extension and stellar winds are important. In both cases non-LTE modeling is a necessity for reliable spectroscopic analyses.

While simple ions (e.g., H, He I, and He II) have been treated routinely in non-LTE for many years it is only recently that advances in computing power, computational techniques, and the availability of atomic data have made it feasible to perform non-LTE line blanketing calculations. Present models, with varying degrees of approximation and sophistication, are now capable of treating the effects of tens of thousands of lines. We review the latest efforts in incorporating non-LTE line blanketing, highlighting recent advances in the modeling of O stars, hot sub-dwarfs, Wolf-Rayet stars, novae, and supernovae.

1. Introduction

An essential tool for understanding stars is spectroscopic analysis. Through spectroscopic analysis we can determine fundamental parameters such as the star's effective temperature, surface gravity, and composition and, assuming the star's distance is known, its luminosity and mass. Other parameters such as mass-loss rate, outflow velocity, rotational speed, and magnetic field strength can also be determined. With these determinations we can place constraints on the evolutionary state of the star. Chemical abundance analyses, for example, can provide information on nuclear processes that

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have occurred deep within the core of the star, providing fundamental tests of stellar evolution.

Hot stars provide special difficulties when it comes to performing spectroscopic analyses. First, due to the combination of low atmospheric densities and high temperatures, the usual assumption of local thermodynamic equilibrium (LTE) is invalid. The non-LTE effect is not subtle, and is readily evident in low resolution spectra of O stars. LTE models of O stars produce H lines that are much weaker than observed. Methods for handling non-LTE calculations in O stars date back to the late 1960's (e.g., Auer and Mihalas 1969).

Second, hot stars emit a significant fraction (in some cases over 90%) of their energy in the extreme UV where it cannot be directly observed. Thus accurate spectroscopic analysis is essential and provides the only method for determining fundamental data.

Third, many hot stars (particularly Pop. I) suffer significant interstellar extinction. In conjunction with the hot temperatures this renders continuum fluxes useless for providing information on stellar temperatures (e.g., Hummer et al. 1988).

Until recently a major deficiency of most codes used to analyse hot stars was the neglect of line blanketing. Only within the last decade, and primarily within the last several years, has progress been made to incorporate non-LTE line blanketing in stellar atmosphere codes. Non-LTE line blanketing is a formidable problem. Ideally tens of thousands of lines should be included and, in addition, the populations of the levels (which number in the hundreds, and perhaps thousands) involved in producing the line transitions must be explicitly solved for. It is the latter requirement, and the lack of the necessary atomic data, which has hindered the incorporation of non-LTE line blanketing into existing codes.

Below we discuss recent advances in the construction of non-LTE blanketed model atmospheres for hot stars. Due to similarities with hot stars, we will also discuss recent work on non-LTE line blanketing in novae and supernovae. For a more general review on the status of non-LTE stellar atmospheres for hot stars the reader is referred to Kudritzki and Hummer (1990).

2. The Need for Line Blanketing in Hot Star Analyses

Recently a large spectroscopic study of O stars was performed by Herrero et al. (1992) using plane-parallel non-LTE non-blanketed model atmospheres. In that study they found that the derived spectroscopic O star masses were systematically lower than evolutionary masses. Since the spectroscopic masses were similar to those obtained using the wind-momentum relationship of Kudritzki et al. (1992), they concluded that this discrepancy was not due to their analysis. The discrepancy, however, is largest for the most evolved stars, which is of concern since the most evolved stars are expected to show the largest effects due to extension and blanketing by the stellar wind. Recently Lanz et al. (1996) argued that metal line blanketing can partly alleviate the mass discrepancy problem. The mass discrepancy is of fundamental importance; if the spectroscopic masses are valid the inferences for stellar evolution are profound.

Wolf-Rayet stars provide another example of where blanketed models are urgently required. Current non-blanketed models are incapable of matching the line strengths of all ionization stages (e.g., N III, N IV and N V in WN stars) simultaneously. This is of concern since it limits the accuracy with which stellar parameters and abundances can be discerned, and consequently also limits the constraints on stellar evolution. Further, the mass-loss rates of W-R stars cannot be derived from first principals. While radiation pressure is generally believed to be responsible (e.g., Lucy and Abbott 1993) this has yet to be demonstrated.

3. Iron

Iron is believed to be the dominant blanketing agent in hot stars, and is also believed to be the primary species responsible for driving mass loss via radiation pressure from hot stars. It is also an important opacity source in stellar evolution models. The importance of Fe is in part due to its relatively high abundance, and is in part due to its atomic structure with its partially filled 3d subshell. As a consequence of the latter, Fe ions give rise to a large number of terms and an enormous number of transitions.

Consider, for example, Fe VI whose three lowest configurations are $3d^3$ (8 terms), $3d^2\,4s$ (7 terms) and $3d^2\,4p$ (19 terms). Transitions between $3d^3$ and the $3d^2\,4p$ configurations lie in the extreme UV (EUV) around 300Å (note that transitions between terms of the 2 lower configurations are forbidden since they both have even parity). The upper configurations are also connected via permitted transitions to the $3d^2\,4s$ terms ($\lambda \sim 1300\mathring{A}$) and consequently there is a strong coupling between the radiation field in the EUV, and that in the IUE UV. In W-R stars this coupling is reflected via the presence of significant Fe emission shortward of 1500 Å — emission that is the direct result of the processing of EUV continuum radiation. A similar situation also holds for other Fe ions (e.g., Fe IV, Fe V, Fe VII). Fortunately the strongest lines do not lie at similar wavelengths so that it is possible to derive a quantitative Fe abundance even in stars where the strong winds broaden that spectral feature so much that individual lines cannot be discerned.

4. Progress Towards Non-LTE Line Blanketed Atmospheres

The principal problem computing non-LTE line blanketed model atmospheres is as follows: To determine the atmospheric structure it is necessary to solve the transfer equation at thousands of frequencies simultaneously with the statistical equilibrium equations. For complex atoms such as iron this is a non trivial task. For example, in Fe IV the first 3 configurations ($3d^5$, $3d^4 4s$, and $3d^4 4p$) alone contain 280 levels (108 terms) and over 8000 transitions! In most objects, several ionization stages of each species (Fe IV through Fe VIII in W-R stars) must be included simultaneously.

Progress in non-LTE blanketed models has been facilitated by several recent developments:

1. Improved methods for solving the statistical equilibrium equations in conjunction with the radiative transfer equations. The most popular of these is the accelerated lambda iteration technique (see reviews by Rybicki 1991, Hubeny 1992)
2. The availability of atomic data. While the Opacity Project (Seaton 1987) has supplied some of the necessary data, there is still an urgent need for further data.
3. Increases in computational power and memory.
4. Better methods for handling level dissolution, and line overlap near series limits (e.g., Hubeny et al. 1994)
5. The concept of super-levels to minimize the number of atomic states whose populations must be solved. This idea was pioneered by Anderson (1989) and is discussed below.

The construction of non-LTE blanketed model atmospheres for hot stars was pioneered by Anderson (1985, 1989). To expedite the construction Anderson used the approach of super-levels. In this approach levels with similar atomic properties (e.g., energies, transition rates) are grouped together and treated as a single *super* level. In the production of the model atmospheres only the populations of the super-levels are solved for. To compute synthetic spectra, populations of individual levels are found using the assumption that the levels making up a given super-level all depart from LTE in an identical fashion. Alternatively, more detailed calculations can be performed for the ion of interest. The code of Anderson has been used to construct non-LTE blanketed model atmospheres for both B and late-type O stars (Grigsby et al. 1992). Anderson also utilized several other approximations, but it is the concept of super-levels which has facilitated the rapid growth in non-LTE blanketed atmosphere codes.

While the basic concept of super-levels is straight forward, different approaches have been adopted for its implementation. In part these implementations simply reflect different philosophies; in part they reflect the different needs of models in different parts of the H-R diagram.

Dreizler and Werner (1993) used the super-level approach to construct the first metal line blanketed model atmospheres for hot stars. Due to the similarity of the atomic properties of the iron group elements they created a generic ion representing each ionization stage of the iron group. Within each ionization stage they used the super-level concept, with each generic ion containing only 6 to 7 super-levels. To treat the multitude of transitions between a pair of super-levels they used an opacity sampling technique. With this procedure they were able to account for line blanketing due to over 1 million lines from Sc through Ni in 5 ionization stages. Their models have been used to interpret the spectra of white dwarfs, and sub-luminous O stars, and allowed them to deduce, for the first time, a reliable Fe abundance and Fe/Ni abundance ratio in the sdO star BD $+28^o4211$ (Haas et al. 1996)

Hubeny and Lanz (1995) have also adopted the super-level approach in conjunction with a hybrid linearization/accelerated lambda iteration method to construct non-LTE model atmospheres for hot stars. To minimize the number of frequencies Hubeny and Lanz used the concept of opacity distribution functions (ODF's). By careful choice of super-levels, transitions between 2 super-levels will occur in a relatively narrow spectral window. Within this spectral window ($\delta\lambda/\lambda < 0.3$) the exact location of individual transitions is generally unimportant. Thus they redistribute the line opacity within this window so that it varies smoothly, and as a consequence they can use relatively few frequencies to sample the opacity variation.

A possible problem with their approach is that the overlap of lines arising from different pairs of super-levels (within the same species, or from a different species) will not be treated correctly. The effect, however, can be minimized by using smaller bands, and/or special treatment of important overlaps (e.g., regions around Ly α). There is also no natural extension to moving atmospheres, where the velocity causes an individual transition to have an influence over a much larger frequency band than its natural bandwidth.

In order to model luminous blue variables (LBVs), W-R stars and other similar objects, Hillier and Miller (1997; Hillier 1996) included another variant of the super-level approach into the non-LTE atmosphere code of Hillier (1990). In their approach, super-levels are utilized only as a means of facilitating the solution of the statistical equilibrium equations, and not the transfer equations.

As in earlier studies, Hillier and Miller group individual levels together to form a super-level, and within this super-level, the departure coefficients are assumed to be identical. No other assumptions are made. In particular,

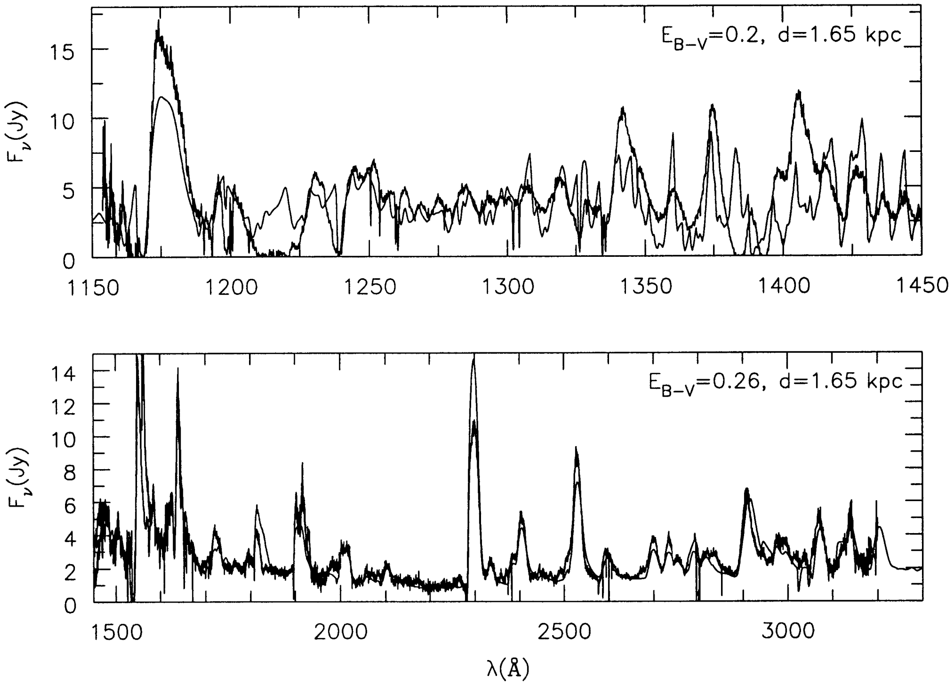

Figure 1. **Comparison of the synthetic spectrum computed using a non-LTE line blanketed model with the IUE spectrum of the galactic WC5 star HD 165763. In this spectral region the strongest spectral features are C III 1175, C IV 1550, He II 1640, and C III 2296. Much of the complex emission/absorption spectrum shortward of 1500Å is due to Fe V and Fe VI.**

individual transitions are treated at their correct wavelengths allowing line interactions, and the effect of velocity fields, to be correctly treated. An advantage of this technique is that LTE is recovered exactly at depth.

To illustrate progress in constructing W-R model atmospheres we compare a model for the galactic WC5 star HD 165763 with IUE observations in Fig. 1. While there are still discrepancies, the overall agreement is excellent. In particular, the models can produce the Fe emission/absorption complex between 1250Å and 1500Å. More importantly, the inclusion of Fe blanketing has helped to alleviate some of the discrepancies found with earlier unblanketed models.

Finally we note that a very different approach towards line blanketing calculations has been taken by Schmutz. Schmutz has utilized the Monte-Carlo code of Abbott and Lucy (1985) to estimate wavelength dependent blocking factors which characterize the influence of line blanketing. These blocking factors are then used to mimic the influence of line blanketing in "normal" non-LTE calculations (e.g., Schmutz 1991, Schmutz et al. 1990). The principal drawback with this approach is that the atomic populations used in the Monte-Carlo code are not necessarily consistent with the radiation field.

5. Novae and Supernovae

While these objects are not "hot" stars their analysis encounters many of the same problems as for W-R stars and LBV's. In particular, they possess atmospheres in which the effects of extension, non-LTE, and velocity fields are crucial for any spectroscopic analysis.

Extensive progress towards non-LTE blanketed modeling of SN has been made by Hauschildt and Ensman (1994), Eastman and Pinto (1993) and Pauldrach et al. (1996). Type II supernovae are simpler to model than Type I, and are more akin to hot stars. Type I are much more difficult to model as they are H/He deficient, and consequently metals dominate both continuum and line opacity. An additional complication of modeling supernovae is that it requires relativistic effects to be incorporated into the radiative transfer.

For novae, Hauschildt and collaborators have made enormous progress over the past 5 years (e.g., Hauschildt et al. 1992, 1994, 1995). In particular they are able to match the UV continuum in novae which is completely determined by the effects of Fe II blanketing. Their calculations indicate that at least 10,000 lines (and perhaps as many as 100,000) must be included if reliable synthetic spectra are to be computed (e.g., Hauschildt et al. 1994). For his models, Hauschildt has used a combination of both LTE and non-LTE. Species such as H are treated in non-LTE while many of the more important blanketing species (e.g., Fe, molecules) are treated in LTE. Later models treat Fe in non-LTE.

6. Conclusion

New computational methods, and the availability of atomic data now allow non-LTE blanketed models to be computed for hot stars, supernovae, and novae. In these models it is possible to handle over tens of thousands of transitions and thousands of levels. These new models should greatly improve spectroscopic analyses, allowing more concise constraints to be placed on stellar and galactic evolution.

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DISCUSSION

Would you comment about models that include wind blanketing?

JOHN HILLIER: Detailed model calculations can be and have been used to provide estimates of wind blocking for plane-parallel static models. However, because of feedback effects and the necessity to explicitly allow for the wind, such methods are always approximate. Ultimately, unified spherical models in which the effects of wind blanketing are explicitly allowed for must be used.

NORBERT LANGER: You mentioned that the winds of WR stars are driven through iron opacity. What is the evidence for this?

JOHN HILLIER: There is no direct evidence. Iron is expected to be the dominant species responsible for the driving because of its large abundance and because its different ionization stages have a large number of transitions around the flux maximum. This is confirmed by the calculations of Lucy and Abbott.