On the Properties of B and A Type Supergiants

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A B S T R A C T

We review the literature of high dispersion studies of late B and early A type supergiants to assess the importance of non-LTE abundance calculations for them. Practically we are interested in learning which elements and species have such calculations been performed and then which of these should be implemented in calculations with plane-parallel LTE model atmospheres. The techniques available for the quantitative modeling of these atmospheres are outlined and some recent results are discussed.

1. What are B and A supergiants ?

Supergiants stars of spectral types B and A are the most luminous visual stars in spiral and irregular galaxies that are currently forming many stars. Also they are potentially attractive distance and abundance indicators being among the most easily observed objects. Early type supergiants which are classified as luminosity class Ia generally show more extreme variations in light, H_{α} profile, and radial velocity than do the Iab and Ib stars. The surface gravity is lower in a higher luminosity star. The spectra of early type supergiants show the light elements (He, B, CNO), the alpha-elements (Ne, Mg, Si, S, Ca, Sc, Ti), the iron-group elements (Cr, Mn, Fe, Ni), and even s-process elements (Sr, Zr, Ba). The spectra of some elements exhibit more than one ionic species, for example, Cr I and Cr II, and Fe I and Fe II.

2. Stellar Atmospheres

B and A type supergiants have large, tenuous gaseous atmospheres. Their high luminosities place them near the limits of radiative and hydrostatic equilibrium. The low atmospheric densities permit the radiation field to affect the atomic population ratios which in turn affect the radiation field through line blocking. Theoretical and observational aspects of the stellar photospheres are covered by the textbooks of Mihalas (1969) and Gray (1992).

The radiative acceleration is exerted on a trace species by a non-LTE radiation field through the species' local opacity and thus it can vary strongly with depth, which results in a chemically stratified atmospheric structure. Significant departures from thermal (equilibrium) ionization occur due to photoionization by an incident radiation field although the ionization balance of tenuous gas is not solely determined by collisional equilibrium according to the Saha equation. In deeper atmospheric layers, both temperatures thermalize, and the equilibrium radiation field assumes an intensity distribution determined by the local kinetic gas temperature. In the upper layers the radiation field dilutes with distance from a point in the atmosphere where the gas becomes sufficiently optically thin, and the radiation temperature decouples from the local thermodynamic conditions.

3. Model Atmospheres

A theoretical stellar atmosphere is based on the physical hypotheses required to describe the transport of energy. Classical plane-parallel atmosphere models, those in hydrostatic, radiative, and steady-state statistical equilibrium, can be highly sophisticated. In plane–parallel model atmospheres all the variables are only a function of depth. When integrating the surface fluxes one has to use the proper geometry. The question is whether the atmosphere is just thin layer or has a substantial depth relative to the stellar radius. Plane-parallel means the atmosphere is thin while spherical means the atmosphere is thick. The effects are seen in the strongest lines especially the Balmer lines. The Balmer jump of a spherical model atmosphere is deeper than a plane-parallel one of the same effective temperature. It requires much more computing power to calculate spherical model atmospheres.

Different computer codes for modeling the atmospheres have been developed over the last 30 years. For LTE, the dominant code is certainly ATLAS (Kurucz 1970, 1979, 1993). The two current common code varieties (9 and 12) include a very detailed description of line blanketing, an important opacity source. But they use different methods for representing atomic and molecular line opacity.

Non-LTE effects on the atmospheric structure become more pronounced at higher temperature, while sphericity and hydrodynamical outflow velocity fields associated with mass-loss are noticeable only for very luminous objects. Sphericity effects on NLTE stellar atmosphere models were studied by, e.g., Mihalas & Hummer (1974), Gruschinske & Kudritzki (1979), and Kubat (1997). Line blanketed spherically extended hydrostatic LTE model atmospheres have been constructed by Fieldus et al. (1990). Aufdenberg (2000) presents a preliminary spherical NLTE model atmosphere for the A2 Ia supergiant Deneb using the PHOENIX code. They used solar abundances and did not consider how changing the photospheric abundances from these values would affect the atmosphere.

The presence of magnetic fields in B and A supergiants are reported in the literature, but require verification with modern high S/N spectra (see, e.g., Severny 1970 and Gerth et al. 1991). Metallicity and microturbulence both affect the line strengths and consequently line blanketing. In supergiant studies microturbulence has been neglected as it is less important than other sources of turbulence. But metallicity strongly affects the stratification and the resulting line profiles.

4. Analysis

The main sequence star Vega (A0V) has been used as a standard. Investigations have employed non-LTE physics. However, Gulliver, Hill & Adelman (1994) showed that it was a fast rotating star seen nearly pole-on. Thus its surface temperature and surface gravity vary between its equator and its poles and one stellar model atmosphere fits to its observables can have produce spurious results. The Vega studies need to be redone by using better representations of its atmosphere. Daflon et al. (1999) derived the LTE and NLTE abundances of CNO and Si in eight Main Sequence OB stars in the CEP OB2 association. The corrections are generally of the order of 0.1 dex or smaller. Given the dependence of the abundances with temperature, the errors due to the temperature uncertainties typically exceeds this number.

Luck & Lambert (1985) found that departures from LTE could enhance the N I lines in the A-type supergiant atmospheres and concluded that the correction for the lines formed in deep layers is near zero, but corrections as large as -1.0 dex were found the lines formed in high layers. The results calculated by Takeda & Takada-Hidai (1995) show that the NLTE corrections are not important for C I and O I lines (W_{λ} < 10 mÅ), and that the corrections are getting small for the lines formed in layers deeper in the atmosphere.

Venn (1995a, b) showed by careful studies of the sources of systematic error that for her less luminous objects, mainly luminosity class Ib and II stars, LTE model atmosphere analyses can indeed be used for spectroscopic analyses. LTE line analysis proved to provide reasonable abundances for some elements, while for others, in particular the lighter elements, NLTE effects were shown to be non-negligible. Some points from her studies are that **1)** the departures from LTE on C and N abundances from her 13 stars range from -0.10 in the F0 stars to -0.50 dex in A3 stars for C. The NLTE correction of N range from -1.0 in the A0 stars to -0.30 dex in the F0 stars, **2)** weak spectral lines for Mg I, Mg II, Si I, Si II, Sc II, Ti II, Cr II, Fe II and Ni I give near-solar abundances, which show little or no trends with T_{eff} or gravity. An examination of Table 1 shows the size of non-LTE effects in Ia stars to II stars and the scatter in the abundances of weak and strong lines.

Table 1. NLTE corrections for Mg line abundances of A type supergiants (Venn 1995a)

λ	HD87737 (AO Ib)		HD 14489 (A2 Ia)		HD 13476 (A3 Iab)		HD 34578 (A5 II)	
Mg I	EW	Δlogε	EW	Δlogε	EW	Δlogε	EW	Δlogε
4702.98	11	0.04	---	---	43	0.02	101	-0.01
5167.32	45	0.05	---	---	121	0.06	---	---
5172.68	70	0.03	69	0.05	174	0.03	219	-0.37
5183.60	86	0.01	72	0.05	193	0.02	242	-0.51
Mg II								
4390.59	85	-0.03	100	-0.04	126	-0.05	---	---
4427.99	31	0.01	24	-0.01	26	-0.02	36	-0.01
4433.99	50	-0.01	40	-0.01	36	-0.02	43	-0.01
4739.59	31	0.03	---	---	30	-0.01	21	0.01
7877.13	115	-0.42	130	-0.30	149	-0.28	126	-0.39
7896.37	178	-0.97	189	-0.51	221	-0.48	210	-0.94

The necessity of invoking NLTE effects for spectral line analysis for lines of several elements was also derived/confirmed in a series of papers by Takeda et al. (2000 and references therein) and Przybilla et al. (e.g., 2003 and 2006 and references therein). According to the Przybilla et al. studies **1)** NLTE corrections for C, N, O and Mg abundances derived from neutral lines are smaller than those from singly-ionized lines, **2)** According to the line abundances of neutral and singly-ionized species, the statistical scatter from weak lines is slightly reduced when compared to LTE analyses, **3)** The systematic NLTE corrections are typically larger (sometimes much larger, as for N I) than the statistical uncertainties, and **4)** The computed NLTE line profiles fit the observations well for the different species at a given elemental abundance. Only for the light elements are distinctive patterns found, with He and N being enhanced, C depleted and O being compatible with the heavier element abundances. NLTE effects become important in blue supergiants, where a strong radiation field at low particle densities favours deviations from LTE (see Table 2).

Table 2. NLTE correction from line abundances given by Pryzbilla et al. (2006)

	β Ori (B8 Ia)	HD 92207 (A0 Iae)	HD 111613 (A2 Iabe)	η Leo (A0 Ib)
C I	---	---	-0.55	-0.36
C II	-0.20	-0.32	-0.27	-0.15
N I	-0.73	-0.69	-0.66	-0.66
N II	-0.29	-0.29	-0.18	-0.15
O I	-0.28	-0.27	-0.17	-0.09
O II	-0.27	---	---	---
Mg I	---	+0.20	+0.15	+0.14
Mg II	+0.03	+0.05	-0.02	-0.08
S II	-0.25	-0.29	-0.17	-0.11
S III	-0.22	---	---	---
Ti II	+0.26	+0.36	+0.23	+0.28
Fe II	+0.38	+0.21	+0.05	+0.05

$\Delta\log\varepsilon = \log\varepsilon_{NLTE} - \log\varepsilon_{LTE}$

NLTE analyses of helium in B and A supergiants are scarce. Contrary to previous results (Lennon et al. 1991, Kudritzki et al. 1987), McErlean et al. (1998) find close to solar helium abundances for the two Galactic supergiants κ Ori (B0.5 Ia) and ε Ori (B0 Ia). Takeda & Takada-Hidai (2000) derived the NLTE abundances relative to solar from He I λ6678 as -0.29 dex for η Leo and as +0.35 dex for β Ori. Przybilla (2002) gives abundances of +0.19 and +0.20 dex, respectively, from eight He I lines.

Non-LTE studies of S II/III, Ti II and Fe II in B and A type supergiants have not been reported in the literature so far.

5. Discussion

Are NLTE effects nonetheless negligible for these B and A type supergiants under consideration? A simple test is to either compare a) weak lines within multiplets (of different elements/ionic species) or b) mean abundances of different ionic species of a chemical element.

1) As most of the lines used in the analysis are on the linear part of the curve-of-growth the line ratios should reflect the ratios of the gf values, if LTE holds. Discrepancies are found in basically every case.

2) Fe I/II/III is a good example to study: while the abundances of Fe I/II are similar, as required by demanding ionization equilibrium, the Fe III abundances can be different by more than a factor of 2 - a clear indicator for NLTE effects in the Fe I/II/III system.

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