High Resolution UV Spectroscopy for the study of A-type Supergiants atmospheres

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ABSTRACT

A-type supergiants are intrinsically the brightest stars at visual wavelengths, and therefore one of the best potential extragalactic distance indicators. These stars present a complex atmospheric physics with a large energy and momentum density of the radiation field, in combination with an extended and tenuous atmosphere and a stellar wind. One of the best tracers of these expanding envelopes are the UV lines of different ions (mainly Mg II, Al II, Si II, C II and Fe II). The scarce works on the UV spectrum of these stars show that high resolution UV spectroscopy and variability analysis are crucial to make progress in the understanding of A-type supergiants atmospheres. A number of important issues remain open. We summarize here the major findings on the winds of A-supergiants in the UV range and the derived open questions. Simultaneously, we address the critical importance of a UV mission to solve them.

Key words: UV astronomy, supergiants, winds, mass-loss, magnetic fields

1. Introduction

A-type supergiants are evolved massive objects (~ 9 – 25M⊙) located in a region of the H-R diagram where evolution is very rapid. Therefore, they are few in number: only about one hundred galactic stars are classified as such. Among these supergiants there is a clear gap between spectral types A5 and F0, which could be related to the evolution of these objects. The evolutionary stage of A-supergiants is still unclear. Although the most extensive work on their abundances suggests that these stars have evolved directly from the main sequence (Venn 1995a), the uncertainties
in these studies are very high, due to the well recognized difficulty of modeling their atmospheres (Venn 1995b; Verdugo et al. 1999a). A recent work by Przybilla et al. (2006) analyses the various effects involved in the modelling of A-supergiants atmospheres (line blanketing, non-LTE, helium abundances, spherical extension, velocity fields, variability). In this work, accurate stellar parameters are determined from a hybrid non-LTE spectrum synthesis technique for four BA supergiants. From the abundances analysis these authors found that three of the stars studied appear to have evolved directly from the main sequence but for the AIIb star, η Leo, a blue-loop scenario is derived.

A-type Supergiants are intrinsically the brightest stars at visual wavelengths, and therefore the best potential extragalactic distance indicators using the wind momentum-luminosity relation (Kudritzki et al. 1999). This relation is derived from the radiation-driven wind theory and mainly based on Balmer line fits.

Radiation pressure is adopted as the dominant driving mechanism for the mass loss of A-supergiants. Unified wind models, which include a solution of the spherical transfer equation in the comoving frame and a non-LTE treatment of hydrogen and helium, were developed by Santolaya-Rey, Puls & Herrero (1997). These models succeed in fitting a number of profiles of the Balmer series for the brightest A-supergiants (Kudritzki et al. 1999), but cannot reproduce neither all the Hα profiles observed, nor their variability. An even more sophisticated model developed by Aufdenberg (2000), which includes non-LTE line blanketing for several metallic lines, failed to fit a typical Hα P-Cygni profile for the brightest A-supergiant Deneb (Aufdenberg et al. 2002).

Stellar winds in A-type supergiants can mainly be studied using the optical spectrum or/and the ultraviolet (UV) spectral range. In the optical all lines seem to be photospheric except Hα which shows a variety of very different profiles: symmetric absorption, P-Cygni, double-peaked or pure emission profiles (Verdugo et al. 1999b). It is in the UV range and particularly in the ultraviolet resonance lines where the presence of a stellar wind is cleanly traced. However, compared to the amount of work devoted to OB stars, the UV spectra of A-supergiants have scarcely been examined (e.g. Lamers et al. 1995, 1978; Praderie et al. 1980; Underhill & Doazan 1982; Hensberge et al. 1982). The most comprehensive studies of A supergiants in the ultraviolet range were performed by Talavera & Gómez de Castro (1987) and Verdugo, Talavera & Gómez de Castro (2006, 2003, 1998) from the observations taken by the International Ultraviolet Explorer (IUE) satellite.

In this article we summarize our findings for the wind of A-type supergiants in the UV range and the remaining open questions, addressing the critical importance of a UV mission to solve them.

2. UV line profiles

The UV spectrum of A-supergiants is characterised by the presence of variable discrete absorption components (DACs; see some examples in Verdugo et al. 1999b) associated
with the resonance lines of different ions, mainly Mg II, Al II, Si II, C II and Fe II. The appearance of these DACs is also related to the luminosity of the star. In Fig. 1 we show three typical observed Mg II[uv1] profiles: symmetric absorption profiles in Ib stars, profiles formed by several components, and a classical radiative-wind profile (without emission) in the Ia and Iab stars. The same behavior is observed in the other lines cited above as is also shown in Fig. 1 for the Fe II[uv1] lines.

Figure 1: Mg II[uv1] (top) and Fe II[uv1] (bottom) in A-supergiants.

2.1. Variability

According to Fig. 1, it may seem that the less luminous A-supergiants (luminosity class Ib) do not show any perceptible trace of mass motion in their spectrum. However, a variability analysis showed the presence of DACs in the ultraviolet Mg II[uv1] lines of two Ib stars as well, which indicates that mass outflow exists.
DACs in the UV spectrum of A-supergiants were initially found only in the brightest A-supergiants. The time scales of variability of these components are of the order of several months. Some examples are shown in Fig. 2.

However, a monitoring programme performed with the IUE satellite in two Ib A-supergiants revealed the appearance and evolution of a single blueshifted component in a much shorter time scale (~ 1 month; see Fig. 3).

The DACs are stronger and more steady in luminous A-supergiants, whereas the Ib stars exhibit these features in a smoother but more variable way.
These two groups are also found from the analysis of the optical spectrum of A-supergiants (mainly from the Hα profile; Verdugo et al. 1999a, 2003).

The existence of these two groups must lie in a different extension, density and properties, in general, between the envelope of the A1a/Iab supergiants and the one of the A1b supergiants. These differences suggest a different evolution history of these stars. In fact, Przybilla et al. (2006) found from the abundance analysis of four A-type supergiants (one Ib star and three Ia/Iab stars), a blue-loop scenario for the only Ib star studied because of a first dredge up abundance ratios, while the other three objects appear to have evolved directly from the main sequence.

2.2. Exceptional behaviour in the Fe II lines

Another very interesting finding from the UV spectrum of A-supergiants which can also be linked with the evolution history of these stars is that there are some luminous stars which present a shortward shifted component at high velocity (\(\sim -150\) km s\(^{-1}\)) but there is not a component at zero velocity (except the interstellar components of the resonance lines) or this component is less intense than the high velocity one. Such behaviour has been detected in the Fe II lines of some bright A-supergiants. In principle, the absence of a component at 0 km s\(^{-1}\) could be due to the fact that
the lines of Fe II are only formed in the wind, which would have a lower degree of ionization than the photosphere. However, this phenomenon is only detected in a few stars of our sample. Most of the A-supergiants show a zero velocity component for the lines of this ion. It is possible that this component at 0 km s\(^{-1}\) is formed also in the wind. In a low density envelope where shocks could be occurring, the spectra would present a pre-shock component (high velocity) and a post-shock component (low velocity). Therefore, the presence or not of such zero velocity component would be related to the density of the wind.

![Figure 4: Fe II [uv62,63] lines in two A-supergiants showing no components at rest (dashed vertical line). The position of a high velocity component (~ -150 km s\(^{-1}\)) is marked with a solid vertical line.](image)

**3. Terminal velocity of the wind**

One of the main predictions of the radiatively driven wind theory is that the terminal velocity of the wind should increase with the escape velocity of the star. However, as shown in Fig. 5, the opposite behavior is found in A-supergiants (Talavera & Gómez de Castro, 1987; Verdugo et al. 1998, 2006).

The terminal velocity, \(v_\infty\), is the mean velocity reached by wind material in regions far away from the star, where acceleration has effectively ceased but interaction with
the interstellar medium has not yet become important. The terminal velocities of the winds of A-type supergiants can be measured directly from the UV P Cygni profiles.

Traditionally, the terminal velocity of a stellar wind has been observationally defined as the modulus of the largest negative velocity seen in absorption in the P Cygni profiles of UV resonance lines. For a P Cygni profile with a deep absorption (saturated profiles) through and a nearly vertical violet edge, the measured edge velocity \(V_{\text{edge}}\) was considered the terminal velocity of the wind (Abbot 1978). However chaotic motions in the winds may extend and soften the vertical violet edge resulting in an overestimation of \(v_\infty\). The difference \(v_{\text{edge}} - v_\infty\) arises from a local velocity field, which has been parameterized as "microturbulence" by Hamann (1980, 1981) and Groenewegen et al. (1989). However, Howarth & Prinja (1989) demonstrate that for saturated ultraviolet line profiles the maximum velocity at which zero residual intensity is recorded \(v_{\text{black}}\) provides an accurate measure of the wind terminal velocity. For stars without saturated profiles, but with identifiable discrete absorption components, the final central velocity reached by these components, \(v_{\text{DAC}}(t \to \infty)\), also provides a good indicator of \(v_\infty\) (e.g. Howarth & Prinja, 1989). However, estimating

Figure 5: Terminal velocity of the wind vs. escape velocity for A-type Supergiants. Empty circles correspond to stars for which the measured terminal velocity is uncertain due to the particular shape of the Mg II[uv1] lines.
this quantity observationally requires frequent UV spectra taken over a sufficiently extensive period, and such a data are only available for a very few stars. Therefore from a single UV spectrum DACs only provide a lower limit to \(v_\infty\).

In order to determine terminal velocities of A-type supergiants is required to analyze several UV spectra taken over a large period. The wavelength or velocity, \(v_{\text{edge}}\), where the violet edge of the Mg II profiles reach the continuum provides an upper limit for the terminal velocities while in most cases the \(v_{\text{DAC}}\) is a lower limit.

### 4. The role of surface magnetic fields

Radiative winds are known to be unstable against small perturbations of the radiative force. However, such small perturbations in the wind cannot account for the aforementioned spectral features. The existence of magnetic fields is a more viable option and has been suggested by many different authors to explain the observations: (1) corotating interaction regions have been suggested to explain the presence of the UV DACs (Mullan 1984), (2) Corotating weak magnetic surface structures could explain the observed H\(\alpha\) variability (Kaufer et al. 1996), and (3) The existence of extended cool loops could account for another phenomenon observed in BA supergiants: High Velocity Absorptions (HVA; see Israeliian et al. 1997). All these facts have motivated us to undertake a search for magnetic fields in the atmospheres of A-supergiants (Verdugo et al. 2005, 2003). Spectropolarimetric techniques have been drastically improved in the last few years allowing to detect weak magnetic fields (of a few hundred gauss) in massive stars. Magnetic fields have been discovered in 5 OB stars (see Henrichs et al. 2005 for a recent review). Specific behaviour of variable stellar wind lines belongs to the well-known indirect indicators of a magnetic field in early-type stars. Typical cyclical variability of the DACs associated to UV lines are thought to be caused by magnetic fields at the base of the flow. Henceforth, analysis of the UV spectra variability is crucial to identify potential magnetic massive stars.

UV high resolution spectroscopy is therefore instrumental to make progress in the different open questions addressed above:

Is the radiation driven wind theory fully applicable to A-type supergiants? In addition, it seems to exist two different groups of A-type supergiants based on luminosity class but only a few UV spectra of luminosity class Ib stars are available. Therefore, high resolution spectra are needed to measure reliable wind parameters and to confirm the possible existence of two different types of A-supergiants. High resolution spectra are also needed to confirm the lack of UV Fe II resonance lines at rest in some of the brightest stars. Moreover, studies of UV variability are decisive to analyse the stellar winds properties, as well as the relevance of surface magnetic fields.
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