Asymmetry in the wind of Ofpe/WN9 stars

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Abstract. Observations have widely demonstrated that most of the O and WR stars have non-symmetric and/or inhomogeneous outflows. Hydrodynamical modelling has also shown that deviations from spherical symmetry are mainly due to radiative instability, stellar rotation and magnetic field, all having a significant impact on stellar evolution. Therefore, spectroscopic and polarimetric detection of asymmetric winds can be used as a feedback on the assumptions of model atmospheres and evolutionary models. In this respect, it would be very important to study wind asymmetries for stars in intermediate evolutionary phases, such as Ofpe/WN9 stars for which little is known. We present and discuss here some observational evidence for wind asymmetry in the case of three Ofpe/WN9 stars in the LMC: BE381, HDE269927c and R99.

1. Introduction

High resolution spectroscopy (in the ultraviolet and optical) and spectropolarimetry observations have shown that massive star winds are commonly variable, asymmetric and inhomogeneous. Two kinds of wind asymmetry have been identified so far:
i) a large scale structure, which shows up as DACs and DISKs, mostly in the wind of O and B stars. DACs (Discrete Absorption Components) characterize the wind of about 80% of the O stars (Howarth & Prinja 1989). They appear in UV P Cygni lines first as broad absorptions at V $\sim$ (0.2 - 0.5)V_∞ and later develop into narrower features as they accelerate towards the wind V_∞. They vary over timescale of $\sim$ 1 hour up to 30 hours as in ζ Puppis and have been observed also in some Be stars with a period of few years (Lamers 1994). Spectropolarimetry indicates that the wind polarization is low in OB main-sequence stars, but significant and also variable in OB supergiants (Schulte-Ladbeck 1994). Recently, Harries & Howarth (1996) have detected a time-constant polarization of $\sim$ 10% in the Hα line of ζ Puppis and interpreted it as due to a two-components wind, with an equatorial disk (or, more mildly, enhancement). Equatorial disks are a typical property of B[e] stars, and their presence provokes splitted emission lines and high wind polarization ($\sim$ 60%, Bjorkman 1994).
ii) A small scale structure, constituted by BLOBs and CLUMPs, which prevails in the wind of WR stars. Emission line profiles are in fact characterized by subpeaks which move with an acceleration of $\sim$ 0.015 km/s^2 from the center to the edges of the line (Moffat 1996). Spectropolarimetry measurements indicate that

the 80% of WR stars is polarized and the variability in %P increases along the sequence WC - WNE - WNL. With respect to their polarization properties, WR stars can then be divided into 4 categories: 1) with spherical and homogeneous wind; 2) with averaged spherical and locally inhomogeneous outflow; 3) with non-spherical and homogeneous wind; 4) with non-spherical and inhomogeneous outflow (Schulte-Ladbeck 1994).

Observations require of course interpretation, and several hydrodynamical models have been proposed to explain wind asymmetries and inhomogeneities. Here, we would like to mention for the large scale structure:
i) the CIR model by Owocki *et al.* (1995) for the appearence of DACs. If the stellar wind is characterized by fast and slow streams (due either to non-radial pulsations or magnetic field) and the star rotates, the streams follow curved trajectories causing the fast material to collide with the slow wind in front of it and form a high density region in the wind which co-rotates with the star. Everytime this region crosses the line of sight it absorbes the stellar radiation and produces an absorption feature which becomes narrower as the region progressively exits from the line of sight. It has been observed, indeed, that DACs patterns repeat over timescale comparable to the estimated rotation period of the star (Kaper & Henrichs 1994).
ii) The WCD/WCZ (Wind Compressed Disk or Zone) model by Cassinelli & Ignace (1996). It is based on stellar rotation and its effect of re-addressing the wind towards the equatorial plane of the star. The shocks developing between the gas flows from above and beyond the equatorial plane confine these flows into a disk in the case of B[e] stars or in a larger zone for those WR stars with higher rotational velocity. However, Owocki (this volume) suggests that, once the WCD has formed, the combination of radiative force, gravity and stellar rotation may drive matter away from the disk towards the stellar poles, so that the higher mass loss “migrates” from the equator to the poles of the star.
iii) The bi-stability mechanism proposed by Lamers & Pauldrach (1991) for B[e] stars. It relies on the bi-stability jump which occurs as the wind optical depth changes from < 1 to > 3. Consequently, the mass-loss rate of the star increases and the wind V_∞ decreases (Pauldrach & Puls 1990). As shown by Lamers & Pauldrach (1991), in a fast rotator star the wind optical depth and, then, the bi-stability jump can be a function of the stellar latitude. This leads to the simultaneous presence of a polar fast wind and an equatorial, slower and dense outflow, i.e. an “equatorial disk”.
Alternative formation mechanisms for stellar disks have been presented by Langer (1997), as a possible effect of the Ω limit which provokes an equatorial expansion of the stellar envelope, and by Drew (this volume), who suggests that, if the accretion disk is still present at the star ignition, the stellar radiation can accelerate the disk matter and turn the disk into an equatorial high mass-loss outflow.

Concerning the small scale structure of massive star winds, Cranmer & Owocki (1996) have shown that perturbations induced by radiative instability may develop at the base of the wind and quickly become non-linear. They produce velocity variations along the radial direction and, consequently, clumpiness in the wind. Slower clumps appear to be denser than those at higher velocity.

The above models indicate then that wind asymmetries are linked to several physical conditions, i.e. radiative instability, stellar rotation and magnetic field, which significantly influence the stellar evolution. An example is given by Fliegner *et al.* (1996) who calculated new evolutionary tracks assuming stellar rotation. The effect is quite striking: depending on the initial stellar mass, rotation drives the tracks on the HR Diagram nearly vertically, at nearly constant T_{eff}, towards higher luminosities with respect to the standard predictions. Moreover, negleting wind asymmetries in model atmospheres seriously affects the determination of the stellar parameters. In this respect, the wind asymmetry observables, i.e. line profiles and polarization measures, provide a powerful feedback on the assumptions of model atmospheres and evolutionary models for massive stars.

2. Asymmetry in the wind of Ofpe/WN9 stars

Observations point out that radiative instability and small scale structure progressively prevail in the stellar wind as the rotation velocity decreases from O to WR stars. As far as the intermediate spectral types are concerned, the Of star ζ Puppis offers a natural link between O and WR stars since it displays both the large and the small scale structures, in the form of an equatorial disk (or wind enhancement) and wind clumpiness, respectively. In the case of Ofpe/WN9 stars, which have been suggested to represent a transition phase between O and WR stars (Nota *et al.* 1996, Pasquali *et al.* 1997a), little is known about their wind geometry because of the lack of good time-coverage of line profile and polarization variability. At this time, all the observational evidence relies on the shape of their H and He lines. In the following sections, we will discuss two examples, based on high resolution spectroscopy in the optical and infrared, concerning three Ofpe/WN9 stars in the Large Magellanic Cloud: BE381, HDE269927c and R99.

2.1. BE381 and HDE269927c

Echelle, optical spectroscopy by Nota *et al.* (1996) allowed us to detect the presence of a red wing in the profile of some H and He lines of BE381, HDE269927c and also R84. The profiles of Hγ, Hβ, HeI λ5876, Hα and HeI λ6678 are plotted for BE381 and HDE269927c in Figure 1 (top) as a function of velocity and with their continuum normalized to unity. This red wing is displaced from the line peak by a velocity of $\sim$ 250 km/s, constant through all the lines and the objects. Interestingly, it is also present in the line profiles of some pre-main-sequence stars (cfr. BP Tau in Figure 1, bottom) observed by Calvert & Hartmann (1992). The authors explained the observed red wing as due to a disk-like geometry of the wind, which would consist of an equatorial disk of accretion and a stellar polar outflow. Therefore, we have suggested that a wind disk-like geometry may apply also to BE381 and HDE269927c, in the sense that the wind of these Ofpe/WN9 stars would have an equatorial and a polar component differing in density and terminal velocity (Nota *et al.* 1996).

Figure 1. Top: Optical H and He line profiles for BE381 and HDE269927c. Bottom: The Hα line observed in BP Tau by Calvert & Hartmann (1992).

2.2. The case of R99

R99 has always been a peculiar Ofpe/WN9 star, because it shows no absorption in the Hδ region (except a weak NIII λ4097, cfr. Bohannan & Walborn 1989) and has a different UV blanketing pattern with respect to the stars of the same spectral type (Pasquali *et al.* 1997a). For this reason, we have analysed its properties in more detail, by fitting its H and He lines in the optical and infrared with the model atmospheres of Schmutz *et al.* (1989). These models combine the "Kiel atmosphere" code with the line blanketing treatment by Schmutz (1991) so that the calculated atmospheres are expanding, line-blanketed in non-LTE conditions and, also, associated with spherically simmetric outflows.

The line profiles of HeII λ4686, HeI λ5876 and Hα (from Nota *et al.* 1996) are plotted in Figure 2 together with the line profiles of HeI λ1.083 μm and HeI λ2.058 μm (from Pasquali *et al.* 1997b). All of the HeI lines present a peculiar P Cygni profile, since the absorption and emission components are detached. The emission component, in particular, shows a sharp profile, very similar to the Hα line. The HeII line appears to be asymmetric, with a red wing analogous to what is observed in BE381 and HDE269927c. The final line fits (dashed profiles) are shown in Figure 3 for the HeII λ4686, Hα and HeI λ1.083 μm lines. They have been obtained for $T_\star$ = 34000 K, $R_\star$ = 43 $R_\odot$, log$\dot{M}$($M_\odot$/yr) = -4.5 and He/H = 0.4/0.6 by number. Except the HeII fit which well reproduces the emission peak and slightly underestimates the blue edge of the observed line, all the other fits fail to model the line emission even when the mass-loss rate and the β exponent of the wind velocity law are varied by a factor of 2 (Pasquali *et al.* 1997b). The residual emission between the observed and modelled lines is characterized by a FWHM of $\sim$ 200 km/s which can not arise from the underlaying HII region at FWHM of 30 km/s (Nota *et al.* 1996). Therefore, we suggest that the failure of our line fitting may be due to the assumption of wind spherical geometry. In other words, R99 may well have a two-components wind, with an equatorial outflow responsible for the bulk of the H and HeI emissions, and a faster polar component producing the HeII emission. If this were the case, our derived stellar properties would underestimate the true stellar temperature and mass-loss rate.

3. Conclusions

Wind asymmetry and inhomogeneity are, observationally, well established for O and WR stars. It would be interesting to study the wind geometry also in stars of intermediate spectral type in order to identify the mechanisms responsible for deviations from spherical symmetry and their impact on the different evolutionary phases. Unfortunately, little is known for the "transition objects" such as Ofpe/WN9 stars. We have discussed some evidence for wind asymmetry in three Ofpe/WN9 stars in the LMC: BE381, HDE269927c and R99, from their H and He line profiles. Of course, more needs to be done for Ofpe/WN9 stars, and spectropolarimetry may settle the question, in terms of the percentage of stars with asymmetric wind, the degree of asymmetry and the variablity of the wind geometry.

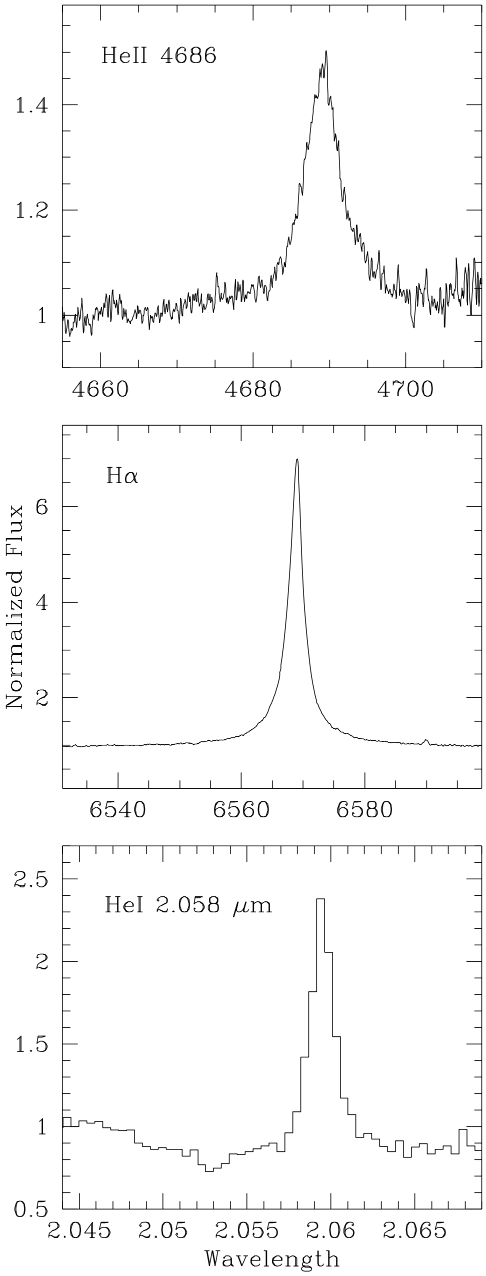

Figure 2. Optical and infrared H and He line profiles for R99.

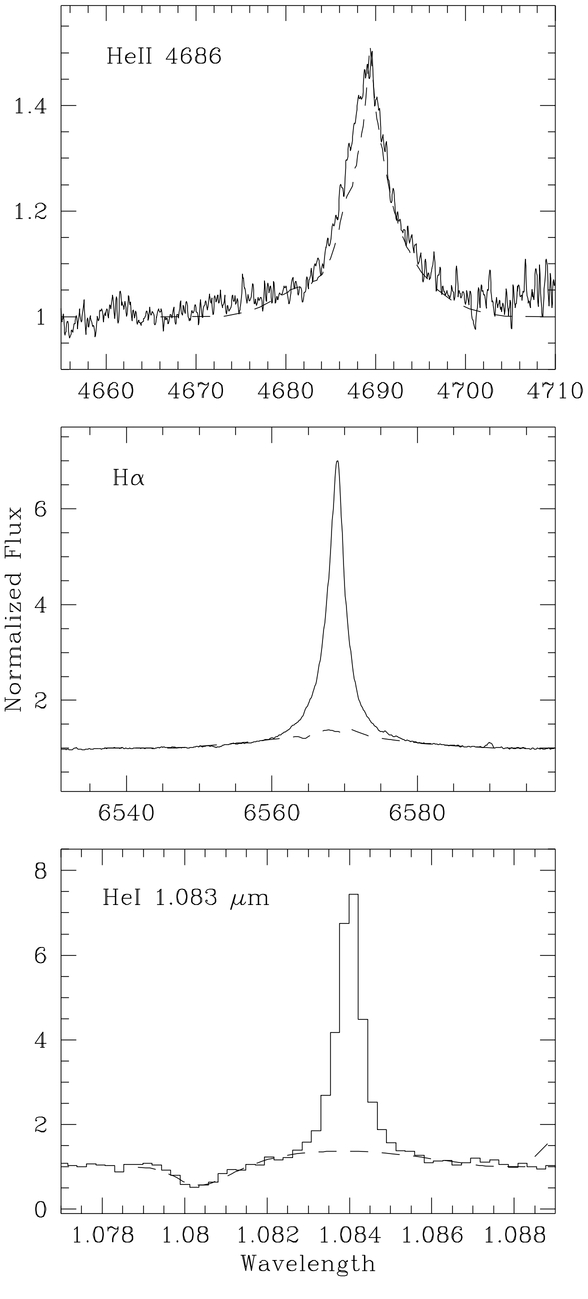

Figure 3. Final fits obtained for HeII λ4686, Hα and HeI λ1.083 μm. The continuous and dashed profiles represent the observed and calculated line.

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