Asymmetry in the Winds of Ofpe/WN9 Stars

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Abstract. Observations have widely demonstrated that most O and WR stars have asymmetric 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, HDE 269927c, and R99.

1. Introduction

High-resolution spectroscopy (in the ultraviolet and optical) and spectropolarimetric observations have shown that massive-star winds are commonly variable, asymmetric, and inhomogeneous. Two kinds of wind asymmetry have been identified so far:
(*i*) Large-scale structure, which shows up as *DACs* and *disks,* mostly in the winds of O and B stars. DACs (Discrete Absorption Components) characterize the winds of about 80% of O stars (Howarth & Prinja 1989). They first appear in UV P-Cygni lines as broad absorptions at $v \simeq 0.2$–$0.5v_\infty$ and later develop into narrower features as they accelerate towards the wind terminal velocity. They vary over timescales of ∼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 ∼10% in the Hα line of ζ Puppis and interpreted it as due to a two-component wind, with an equatorial disk (or, more mildly, enhancement). Equatorial disks are a typical property of B[e] stars, and their presence results in split emission lines and high wind polarization (∼60%; Bjorkman 1994).

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(*ii*) Small-scale structure, composed of *blobs* and *clumps,* which prevails in the wind of WR stars. Emission-line profiles are in fact characterized by sub-peaks which move with an acceleration of $\sim$0.015 km s^{-2} from the centre to the edges of the line (Moffat 1996). Spectropolarimetric measurements indicate that the 80% of WR stars are polarized, and the variability in percentage polarization increases along the sequence WC–WNE–WNL. With respect to their polarization properties, WR stars can then be divided into 4 categories: (1) spherical and homogeneous winds; (2) time-averaged spherical, but locally inhomogeneous, outflows; (3) non-spherical and homogeneous winds; and (4) non-spherical and inhomogeneous outflows (Schulte-Ladbeck 1994).

Observations require interpretation, of course, 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 fields) and the star rotates, the streams follow curved trajectories, causing the fast material to collide with the slow wind in front of it to form a high-density region in the wind which co-rotates with the star. Every time this region crosses the line of sight it absorbs 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 timescales comparable to the estimated rotation periods (Kaper & Henrichs 1994).

(*ii*) The WCD/WCZ (Wind Compressed Disk or Zone) model by Cassinelli & Ignace (1996). This 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 below 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 velocities. However, Owocki et al. (1998) suggest that, once the WCD has formed, the combination of radiative forces, 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. This 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 terminal velocity decreases (Pauldrach & Puls 1990). As shown by Lamers & Pauldrach (1991), in a fast-rotating star the wind optical depth and, therefore, 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, 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 produces an equatorial expansion of the stellar envelope, and by Drew (1998), who suggests that, if the accretion disk is still present at the star's ignition, the stellar radiation can drive 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 in the radial direction and, consequently, clumpiness in the wind. Slower-moving clumps appear to be denser than those with higher velocity.

The above models indicate then that wind asymmetries are linked to several physical conditions, i.e., the radiative instability, stellar rotation, and magnetic fields, 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 almost vertically, at nearly constant $T_{\rm eff}$, towards higher luminosities with respect to the standard predictions. Moreover, neglecting 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 measurements, provide a powerful feedback on the assumptions of model atmospheres and evolutionary models for massive stars.

2. Asymmetry in the Winds of Ofpe/WN9 Stars

Observations indicate that the 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 large- and 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 as representing 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 temporal 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, HDE 269927c, and R99.

2.1. BE381 and HDE 269927c

Optical echelle spectroscopy by Nota et al. (1996) allowed us to detect the presence of a red wing in the profiles of some H and He lines in BE381, HDE 269927c, and also R84. The profiles of Hγ, Hβ, He I λ5876, Hα, and He I λ6678 are plotted for BE381 and HDE 269927c in Fig. 1 (top) as a function of velocity, with the continua normalized to unity. This red wing is displaced from the line peak by a velocity of $\sim$250 km s^{-1}, constant through all the lines and the objects. Interestingly, it is also present in the line profiles of some pre-main-sequence stars observed by Calvert & Hartmann (1992; cf. BP Tau in Fig. 1, bottom). 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 disk-like wind geometry may apply also to BE381 and HDE 269927c, in the sense that the winds of these Ofpe/WN9 stars would have an equatorial and a polar component differing in density and terminal velocity (Nota et al. 1996).

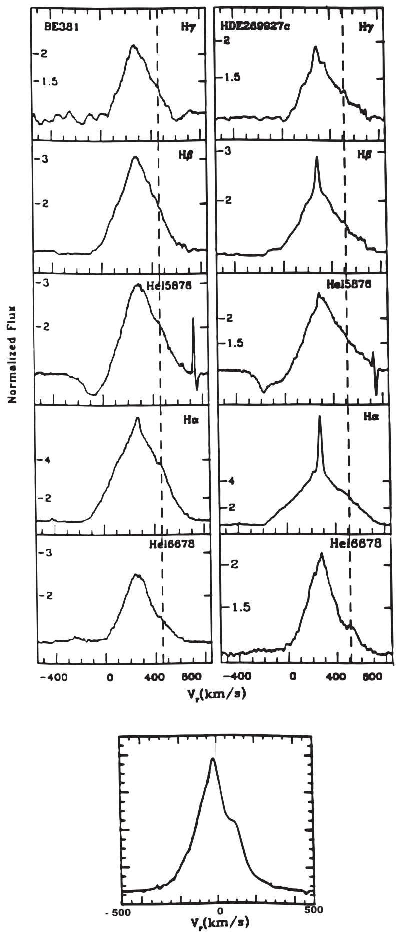

Figure 1. Top: Optical H and He line profiles for BE381 (left) and HDE 269927c (right). Bottom: The Hα line observed in BP Tau by Calvert & Hartmann (1992).

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 weak N III λ4097; cf. 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 symmetric outflows.

The line profiles of He II λ4686, He I λ5876, and Hα are plotted in Fig. 2 (from Nota et al. 1996) together with the line profiles of He I $\lambda1.083\mu$m and He I $\lambda2.058\mu$m (from Pasquali et al. 1997b). All of the He I lines present a peculiar P-Cygni profile, since the absorption and emission components are 'de-

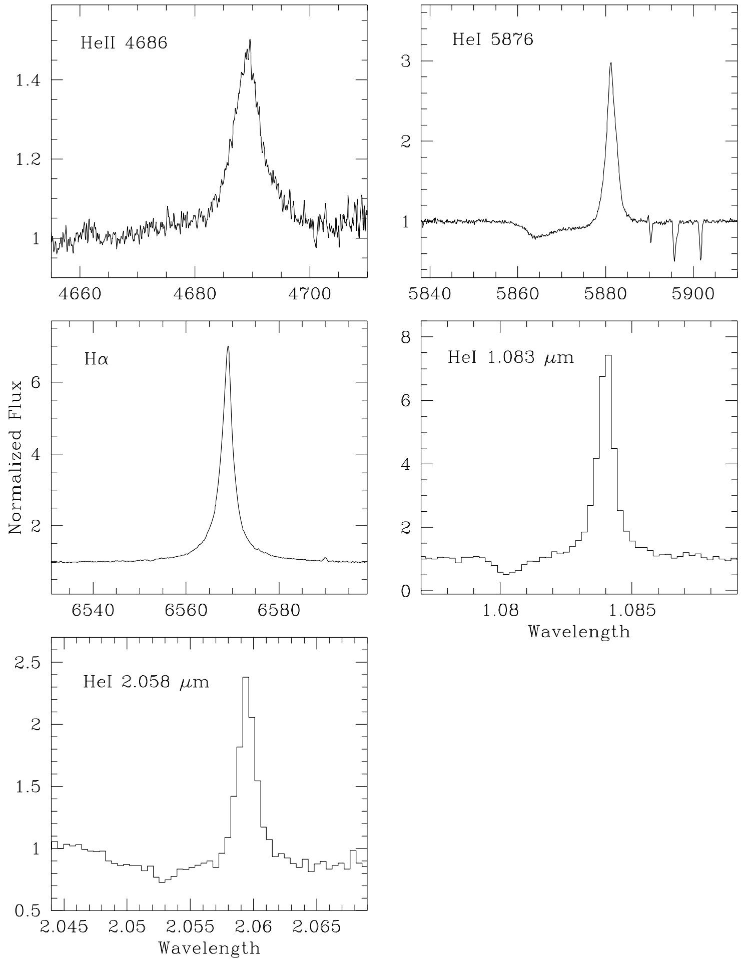

Figure 2. Optical and infrared H and He line profiles for R99.

tached'. The emission component, in particular, shows a sharp profile, very similar to the Hα line. The He II line appears to be asymmetric, with a red wing analogous to those observed in BE381 and HDE 269927c. The final line fits (dashed profiles) are shown in Fig. 3 for the He II λ4686, Hα, and He I $\lambda 1.083\mu$m lines. They have been obtained for $T_* = 34\,000$ K, $R_* = 43 R_\odot$, $\log(\dot{M}/[M_\odot\ \mathrm{yr}^{-1}]) = -4.5$, and He/H = 0.4/0.6 by number. Except for the He II fit, which reproduces the emission peak well 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^{-1}, which can not arise from the underlying H II region (FWHM 30 km s^{-1}; Nota et al. 1996). Therefore, we suggest that the failure of our line fitting may be due to the assumption of spherical geometry. In other words, R99 may well have a two-component wind, with an equatorial outflow responsible for the bulk of the

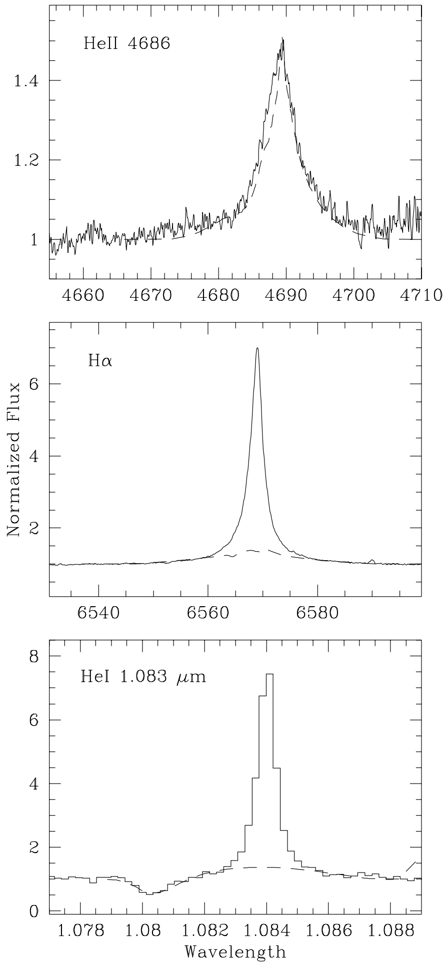

Figure 3. Final fits obtained for He II λ4686, Hα and, He I $\lambda 1.083\mu$m. The continuous and dashed profiles represent the observed and calculated line profiles.

H and He I emissions, and a faster polar component producing the He II emission. If this were the case, our derived stellar properties would underestimate the true stellar temperature and mass-loss rate.

3. Conclusions

Wind asymmetries and inhomogeneities are, observationally, well established for O and WR stars. It would be interesting to study the wind geometry in stars of intermediate spectral type as well, in order to identify the mechanisms responsible for deviations from spherical symmetry and to investigate 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, HDE 269927c, and

R99), based on 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 winds, the degree of asymmetry, and the variablity of the wind geometry.

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Discussion

Owocki: I think that the evidence among many types of rapidly-rotating stars for equatorial density enhancements, probably even disks, is very strong. In a way that's a real puzzle, given the results I showed yesterday [p. 237], because you don't seem to be able to get that in the natural way everyone thought possible with the 'wind-compressed disk' model, although there may be many ways to get a disk – what we saw on Monday [Drew, p. 14], for example, where you have an equatorial accretion disk modified by radiation.

As a theoretician, what I'd like to ask the observers is this: is it possible that when we see a slash star we are viewing a star, which might otherwise appear more normal, at some special orientation? Arguments about the terminal velocity being tied to the escape velocity, for example; these assume more-or-less spherically symmetric, steady-state outflows. If you were accelerating a wind from the inner part of a disk, say, where the escape velocity would be very small, you could get a very low terminal velocity. Could you use this to explain the slash stars?

Pasquali: Well, my opinion is that for slash stars we have to go to spectropolarimetry to test what I've presented; and we're doing that.

Bohannan [to Owocki]: There are only ten slash stars known, and there are only three of the related O Iafpe stars in the Galaxy, so we're not looking at large numbers. There's only one of the slash stars that's like R99, and making up three groups out of ten stars... what I'm saying is that this isn't something that's common in stellar evolution. Your point is well taken that we have to be careful about making generalities about stellar evolution from these stars.

Nota: LBVs are the same.

Harries: As a general point, if you use spherically-symmetric models to fit emission-line profiles from winds with large-scale asymmetries – and get satisfactory fits – then you *over*-estimate the mass-loss rates, because *any* asymmetry increases the line emission over the spherically-symmetric case.

Walborn: Just to add an historical comment, back in the '30s or '40s Struve found He I λ3889Å in HD 152408, which he considered unidentified because it was a 'detached', very blue-shifted component, similar to what you have in R99. This problem was later discussed by Hutchings; $\lambda\lambda$3889, 10830, and to some extent λ5876 are metastable or quasi-metastable lines that are very sensitive to dilute structure, and may need special consideration because of that. You could imagine that the detached 'dips' in Fig. 2, for example, might arise from a spherically symmetric structure with some sort of high-velocity structure in the line of sight.

Pasquali: But then how would you explain the red wing, which is present not only in He II λ4686 but also λ1640?

Walborn: Well, I really just wanted to point out that it would be interesting to try to take into account these metastable effects.

Conti: It looks like we're now going in the direction of non-spherical situations, as has happened for Wolf-Rayet stars. Presumbly the stars involved are those with high rotation, so it's interesting to look at that. This brings up a couple of puzzles in my mind, one of which is that it's curious that the high rotation manifests itself once the star has evolved away from zero age, where the radius has got larger and, if anything, you'd imagine rotation to be *less* important. The second thing is, presumably we're concerned with the high-velocity tail of the $v_e \sin i$ distribution, and then the question is what is happening to those stars when they're on the main sequence; maybe they're the Oe stars, and have disks already on the main sequence.

Crowther: Can I just re-emphasize that R99 really is unique; I don't think it should really be associated with the rest of the slash stars.