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Spectroscopic and photometric variability of O and Wolf-Rayet stars

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Abstract

Low-level line profile variability in the optical domain is a ubiquitous feature of O, Of and Wolf-Rayet type stars. This variability can arise from pulsations, from magnetic fields or wind structures (both small and large scales). For main-sequence O-type stars, the spectra display many absorption lines that provide stringent diagnostics of photospheric features. However, as the stars evolve off the main-sequence towards the Of and Wolf-Rayet stage, the stellar wind densities (and hence the wind optical depths) increase dramatically. The wind eventually dominates the formation of the entire spectrum rendering the investigation of photospheric structures more ambiguous. We discuss the observational analyses of the spectroscopic and photometric variability of massive stars of spectral type O, Of and WR. In particular, we highlight the search for a connection between the photospheric and the wind variability.

Optical spectra of O, Of and Wolf-Rayet stars

Main sequence O-type stars have optical spectra that are dominated by rotationally broadened photospheric absorption lines (mainly H I, He I and He II as well as some weaker metallic lines). The stellar winds of O V stars are usually not sufficiently dense to produce strong and broad emission lines in the optical domain. On the other hand, Of-type objects are defined as O-stars showing some selective lines in emission (N III $\lambda\lambda$ 4634-41 and He II λ 4686). These Of stars are believed to be somewhat more evolved supergiants with denser stellar winds. As the stars evolve, they become Wolf-Rayet stars of the WN sequence with spectra dominated by broad helium and nitrogen emission lines formed in a very dense expanding wind. Later on, these stars evolve towards the WC stage where the optical spectra are dominated by helium, carbon and oxygen lines. The O $\rightarrow$ Of $\rightarrow$ WN $\rightarrow$ WC sequence not only reflects a progression in the evolutionary stage of the star, but also in its wind parameters. Indeed, typical values of the stellar and wind parameters and wind densities are given in Table 1.

An immediate consequence of the progression in stellar wind density concerns the observability of the stellar surface. In fact, in the case of O V stars, the stellar photosphere can be observed directly in the optical domain and deformations of this photosphere, e.g. due to pulsations, can be Doppler mapped through the investigation of the variability of rotationally broadened photospheric absorptions. For Wolf-Rayet stars, on the contrary, the winds are optically thick so that there are no purely intrinsic photospheric absorptions left in their spectra. As a result, any information from the stellar core is 'filtered' by the wind before it reaches the observer. Actually, the situation is even more complex since these stellar winds are highly clumped media (see below). An intermediate situation is observed in Of stars where the photosphere still produces an observable signature in the spectrum whilst the denser regions of the stellar wind produce optical emission lines such as Hα and He II λ 4686.

Table 1: Typical wind parameters of various categories of early-type stars. In this table, v_∞ is the wind's terminal velocity, R_* the stellar radius, β the exponent of the wind's velocity law and $\dot{M}$ the mass loss rate of the star. $\rho(2\,R_*)$ is the wind density at $2\,R_*$. The parameters listed here refer to clumped model atmosphere fits to the spectra of HD 96715 (O4 V), HD 190429A (O4 If$^+$) (both from Bouret et al. 2005), WR 78 (WN7, Hamann et al. 2006) and Br 43 (WC4, Hamann & Koesterke 1998).

Spectral type	v_∞ (km s^{-1})	R$_*$ (R$_\odot$)	β	$\dot{M}$ (M$_\odot$ yr^{-1})	$\rho(2\,R_*)$ (g cm^{-3})
O4 V	3000	12.0	1.0	0.25×10^{-6}	3×10^{-15}
O4 If$^+$	2300	19.6	0.8	1.80×10^{-6}	9×10^{-15}
WN7	1385	16.7	1.0	79.0×10^{-6}	1×10^{-12}
WC4	2800	1.06	1.0	95.0×10^{-6}	1.5×10^{-10}

The spectroscopic variability of single O-type stars

Spectroscopic variability is a widespread phenomenon among presumably single early-type stars. On the one hand, long time series of UV spectra of OB and Wolf-Rayet (WR) stars obtained with the *IUE* satellite revealed a strong variability of those lines that are preferentially formed in the wind (see e.g. Prinja et al. 1998). This variability usually takes the form of irregularly recurring discrete absorption components (DACs) or periodic global modulations of the intensity of the absorption components. Both kinds of features are interpreted as being due to large-scale structures in the stellar wind. The most intensively monitored O-stars display probably cyclic variability on time scales of a few days, i.e. exceeding the typical flow times of the winds (see Blomme 2009). On the other hand, the monitoring of a sample of 30 O-type stars with spectral types between O4 and O9.7 and luminosity classes V to I in optical spectroscopy revealed that 77% of the targets display significant line profile variability on time scales ranging from several hours to about one week (Fullerton et al. 1996). In their campaign, Fullerton et al. (1996) found all supergiants to display line profile variability (lpv), whilst non-variable stars were preferentially found among the main-sequence objects. Although a large fraction of the variability must arise in the wind, Fullerton et al. found a good agreement between the location of the stars showing lpv and the theoretically expected pulsational instability strip. This finding suggests the existence of a link between the variability at the level of the photosphere and in the wind.

As long as the *IUE* observatory was available, a powerful approach was to organize coordinated multi-site observations that combined UV resonance lines (e.g. Si IV, C IV, N V) and H I, He I, He II optical lines. These campaigns revealed that in many cases, the cyclical wind variability can be traced down from the outer wind regions (where the P Cygni troughs of the UV resonance lines are formed) to the inner wind region where Hα is formed (see e.g. the cases of ξ Per, O7.5 III(n)((f)) and 68 Cyg, O7.5 III:n((f)) discussed by Kaper et al. 1997 and de Jong et al. 2001). Since such campaigns are no longer possible, the current focus is mainly on the optical domain. For O-type stars, the optical spectra include photospheric absorption lines as well as some emission lines (Hα, He II λ4686,...) that provide an important diagnostics of the inner regions of stellar winds. In fact, these emission lines are formed through radiative recombination which has a ρ^2 dependence. These lines are thus very sensitive to the high density, strongly accelerating part of the wind close to the stellar surface.

Whilst the DAC features discussed in the previous paragraphs are believed to be due to large-scale wind structures, additional emission line profile variations can also occur as a result of stochastic fluctuations of the number of small-scale turbulent clumps propagating outwards with the wind. Evidence for the existence of such a process in O-stars was found in the emission lines of ζ Pup (O4 Ief) by Eversberg et al. (1998) and HD 93129A (O3 If*) by

Lépine & Moffat (2008) in the form of low-level (a few percent) emission features that move away from the line core to the blue or red wing of the line.

The search for a photospheric connection?

As we have seen above, there is overwhelming evidence that the large-scale structures in the winds of early-type stars arise from, or extend into, the deepest layers of these winds. Also, from an observational point of view, it is found that a detectable photospheric variability is a sufficient condition for the presence of detectable wind variability, whilst the reverse is not true. These considerations then lead to the question whether there exists a connection between the wind features and the photospheric variability. The search for this *photospheric connection* thus became a kind of quest for the holy grail in early-type stars' astrophysics.

Such a photospheric connection could result

- either from magnetic fields rooted in the photosphere that would force part of the wind into corotation with the star (Babel & Montmerle 1997, ud-Doula & Owocki 2002),
- or from nonradial pulsations (NRPs) that perturb the stellar wind and combine with the instability of the latter to produce structures (Owocki & Cranmer 2002).

On theoretical grounds, it is expected that a perturbation of the photospheric conditions leads to the formation of structures in the wind. Indeed, in the commonly accepted radiation pressure wind driving paradigm for O-star winds, the mass loss per unit surface area is directly proportional to the surface radiation flux F. Hence, in a pulsating star with spatial or temporal variations in F, modulations of the overlying stellar wind are expected. The base variations induce a wind structure with fast rarefactions that ram into slower flows inducing a shock that compresses material into a dense shell (Owocki & Cranmer 2002).

Searching for such a connection is not an easy task. As we have seen above, the optical domain (offering simultaneous access to photospheric absorption lines and emissions or P Cygni features from the deeper wind layers) is ideally suited for such a research. However, the variability of O-type stars can be quite complex, involving many different time scales. This brings up one of the major problems of the NRP scenario to explain the wind variability. Indeed, whilst several cases exist where DACs and NRPs have been observed (e.g. λ Cep, O6 Ief and ξ Per, de Jong et al. 1999, 2001), DACs or global modulations of UV absorption troughs have recurrence time scales of several days ($\sim$ 2 d for λ Cep, 2.087 d for ξ Per) whilst NRPs occur with much shorter periods of several hours ($\sim$ 6.6 and 12.3 h for λ Cep and 3.45 h for ξ Per).

Probably the most secure examples of NRPs in O-type stars are provided by the two rapidly rotating O9.5 V stars ζ Oph (Walker et al. 2005) and HD 93521 (Rauw et al. 2008). For HD 93521, two NRP periods (1.75 and 2.89 h) are clearly detected in the He I features, including the He I λ 5876 line. However, the latter line as well as Hα[1] are dominated by variations at much longer time scales (of the order of one day, see Fig. 1). It must be stressed that *IUE* observations did not reveal any variability of the wind lines on the pulsational time scales (Howarth & Reid 1993). A similar conclusion applies to ζ Oph (O9.5 V) where Howarth et al. (1993) found no evidence for a direct role of the well-established NRPs in the triggering of the DAC events. The DACs have a recurrence time of about 20 h, much longer than the periods of the NRPs which are 3.34 h and several other hourly periods (Kambe et al. 1997, Walker et al. 2005).

Another issue with the NRP model is that fast rotators have shorter DAC recurrence times and it has been suggested that the recurrence time scales with the rotational period of the star. Such a scaling is not expected if the DACs are triggered by single NRP modes

[1] The Hα line displays emission wings that are likely formed in an equatorial wind.

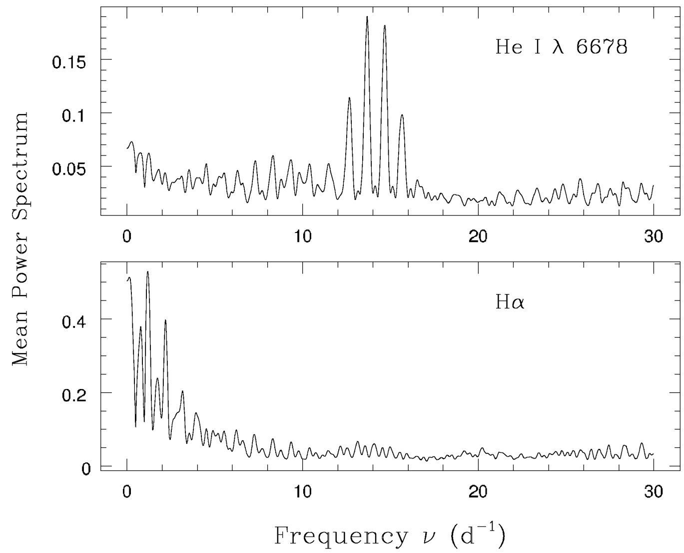

Figure 1: Comparison between the power spectrum of the variations of the He I λ 6678 and Hα lines of HD 93521. Whilst the former is dominated by two pulsational frequencies at 13.7 and 8.3 d^{-1} along with their neighbouring one-day aliases, the latter is dominated by longer time scale variations (Rauw et al. 2008).

or by beating of several pulsation modes. This argument would make magnetic fields more serious candidates since an oblique magnetic rotator model could force part of the wind into corotation with the star.

However, the magnetic field scenario also faces a number of problems. One of the most embarrassing issues is the rarity of direct detections of strong magnetic fields. Indeed, to date, only two O-stars (θ^1 Ori C, O7 V, and HD 191612, O6.5-8 f?p; Donati et al. 2002, 2006) are known to display a strong magnetic field of the order of 1 kG. In both cases, the measured magnetic field strengths are sufficient to significantly affect the dynamics of the stellar wind. Both stars display strong periodic line profile variability, but on very different time scales: 15 d for θ^1 Ori C and 528 d for HD 191612 (see Nazé et al. 2008 for a full comparison between the properties of these two stars). According to the oblique magnetic rotator model, these periods would have to be interpreted as the rotational periods of the stars, but this result would then imply that, at least in the case of HD 191612, the width of the absorption lines must be unrelated to the actual rotational velocity. In the majority of the cases, attempts to directly detect magnetic fields responsible for the large-scale wind structures failed (e.g. de Jong et al. 2001, Schnerr et al. 2008). As a conclusion, strong ($\geq$ 500 G) fields are certainly not widespread among normal O stars although weaker (more difficult to detect) fields might actually still be sufficient to modulate the stellar winds.

Another issue comes from multi-epoch observations of Oef stars (Rauw et al. 2003, De Becker & Rauw 2004). These are rapidly rotating Of stars with double-peaked He II λ 4686 emission lines (the most prominent examples of this sparse category are ζ Pup and λ Cep). In the case of BD+60° 2522 (O6.5 ef), variations were detected on time scales of 2 to 3 d.

However, both the time scales and the variability pattern were found to be epoch dependent. Moreover, in some cases, the pattern of variability (restricted to a limited range in velocity) is not consistent with a corotating structure.

A possible breakthrough in the search for a photospheric connection was obtained by Kaufer et al. (2006). These authors investigated the line profile variability of the photospheric absorption lines of the B0.5 I supergiant HD 64760. The photospheric absorptions of Si III λ 4553 and He I λ 6678 display travelling pseudo absorptions and emission features with a peak-to-peak amplitude of 1%. The Fourier analysis revealed three significant periods at 4.810, 4.672 and 4.967 h likely associated with p mode nonradial pulsations. The observed periods are closely spaced in time in the observer's frame of reference. Hα is dominated by longer time scale variations of the order of days (including the 2.4 d period seen in the UV data of this star, see Blomme (2009) and references therein). The beating of the two strongest of the closely spaced NRP pulsation modes leads to a retrograde beat pattern with two regions of constructive interference diametrically opposite on the stellar surface with a beat period of 6.8 d ($\nu_{\text{beat}} = \nu_2 - \nu_1$). While it must be stressed that the beat period of 6.8 d does not match the 2.4 d periods (it is actually closer to the DAC recurrence time scale), it nevertheless provides a promising avenue to search for a link between NRPs and large-scale wind structures.

The spectroscopic variability of single WR stars

In the case of WR stars, the entire spectrum is generally formed in the wind and any possible star-surface signal is necessarily filtered by the part of the wind below the zone of formation. The situation is rather complex because the winds of these stars present a marked structure: low ionization lines being statistically broader and formed in outer layers. The emission lines themselves are formed over a volume corresponding to a large range of depths in the wind (or distance from the hydrostatic core). According to the standard model of Hillier (1988, 1989), the formation region, in a WC5 star, of the He II λ4542 line ranges from 3 to 8 stellar radii whereas for He I λ10830, it corresponds to 10 to 100 stellar radii. In a WN5 star, the N IV λ4058 line is formed between 1.8 and 5 stellar radii. Each wavelength in the profile of a typical emission line corresponds to one projected line of sight velocity and thus to layers of different depths in the wind. So, in addition to the filtering phenomenon, some blurring of the signal is also to be expected.

From the observational point of view, variability of WR emission lines is quite widespread, particularly among WC stars. It mainly consists in the presence of numerous, relatively narrow emission subpeaks on top of the main emission profiles; these subpeaks tend to move away from the center of the line. They are interpreted as originating in small-scale wind structures of higher density propagating radially outwards. These features, sometimes called blobs, are stochastic in time and are often associated with the small-scale clumping of the wind. They have been noticed in WR stars well before the two examples identified among O stars, most probably due to a better marked contrast. In the majority of the stars, no determinism has been detected in this phenomenon. It is clear that this additional behaviour is a source of stochastic variability that will further contribute to hide any possible deterministic signal coming from the stellar surface (Robert 1994; Lépine & Moffat 1999 and references therein).

In the UV domain, the absorption components of P Cygni profiles of most of the lines are saturated and no flux is emitted in the absorption trough which is at zero residual intensity. Therefore, the equivalents of O-star DACs are much more difficult to detect. Very often, the variability is only visible at or near the terminal velocity. Actually, the only report of DACs in WR stars is for WR 24 (WN6ha, Prinja & Smith 1992) where recurrent (periodic?) wide features are seen moving outwards in the unsaturated He II λ1640 line. The similarity with the case of O stars is only partial and another interpretation could apply. It is interesting to note that we have been able to outline the existence of inhomogeneities in the wind of

WN8 stars on the basis of particularly narrow transient dips superimposed on the absorption component of the He I P Cygni profiles (see Fig. 2 of Gosset et al. 2005).

Although line-profile variations are usually considered as stochastic (in single WR stars), a couple of WN stars present a different behaviour. Two of the best studied WN stars seem to have a semi-deterministic behaviour. Actually, the line profile exhibits a pattern of subpeaks that look randomly distributed and evolving in a stochastic way. However, after a typical time-scale, the very same profile is displayed again by the line. It recurs in a periodic way a few times but after several cycles, the structure slowly evolves. The coherency is only lasting typically 10 cycles or so. The phenomenon is explained by large-scale structures distributed over the envelope of the star and corotating with the star. These structures are slightly evolving with time on a longer time-scale than the rotation period. There are clues indicating that they are deeply rooted close to the stellar surface. Such corotating features are claimed to be present in WR 6 (WN4, Morel et al. 1998) and in WR 134 (WN6, Morel et al. 1999). Some authors also proposed WR 1 (WN4), but the discussion is not closed (Flores et al. 2007; Chené et al. 2008). The latter authors proposed to use this property to investigate the rotational velocity of WR stars. In any case, these slowly moving features constitute a further disturbing factor in the analysis of the spectroscopic variability of WR stars. One still cannot reject the idea that the large-scale structure is related to pulsations (through beating) on the surface.

The photometric variability of single WR stars

For a long time, the WR stars have been known to be photometrically variable and this phenomenon was studied with the hope to unveil the exact nature of these stars. Various limited surveys concluded that the WR stars are presenting a global photometric dispersion of the order of $\sigma = 0.003$–0.030 mag (intrinsic to the star, see Moffat & Shara 1986, Lamontagne & Moffat 1987, Gosset et al. 1994, Marchenko et al. 1998). Very few WRs are not to be listed as variable but, from the ground, differential photometry has difficulties to be more precise than $\sigma \sim 0.003$ mag. The WR variability presents a distribution of the power on the various time scales that is reminiscent of white (or slightly red) noise, i.e. a predominantly stochastic behaviour. The presence of some determinism (periods?) has been claimed in a few cases but full agreement has never been reached on a single WR star. Later spectral types are more variable than early-type ones. Stars from the WC sequence are slightly less variable than those of the WN sequence. In addition, the latter includes the WN8 subclass which contains by far the most variable objects (0.1 mag peak to peak). It is interesting to notice that WR 135 (WC5), one of the less photometrically variable ones, is highly variable from the spectroscopic point of view (blobs).

The flux in a visible broadband filter is essentially determined by the photons from the continuum (formed in deep wind layers but usually not down to the surface; Hamann et al. 1995). It could thus be sensitive to the signal coming from the surface of the star. For this reason, astronomers scrutinized the WR lightcurves to discover short time variations. Actually the fundamental mode of pulsation is expected to have a period of 10-60 m whereas oscillation modes with periods in the range 0.2-1.0 d could also be present (Maeder 1986, Noels & Scuflaire 1986, Scuflaire & Noels 1986, Cox & Cahn 1988, Glatzel et al. 1993). Table 2 is a critical compendium of the WR stars having been convincingly claimed to exhibit short-term variations. Discarding the possible binary systems, there are very few good examples. Most of the time, the periodic behaviours were ephemeral. The variations around 10 m reported for WR 40 (WN8h) have never been confirmed but were refuted on various occasions (Bratschi & Blecha 1996, Martinez et al. 1994, Marchenko et al. 1994). The short periodicity attributed to WR86 could actually be due to a pair of periods and originate in a previously unresolved ($0.''2$) B-type visual companion belonging to the β Cephei class (Paardekooper et al. 2002).

Table 2: A compendium of WR stars claimed to have exhibited a short-period variation.

Object	Period	References	Remarks
Cyg X-3	4.8h	-	WR+compact comp.
WR46 (WN3p)	7h	Veen et al. 2002	Probable binary
WR40 (WN8h)	627s	Blecha et al. 1992	Never confirmed
WR6 (WN4)	20-30m	Bratschi & Blecha 1996	During 1 night
WR78 (WN7h)	25m	Bratschi & Blecha 1996	During 1 night
WR111 (WC5)	20m	Bratschi & Blecha 1996	During 2 nights
WR86 (WC7)	3.5h	van Genderen et al. 1990	With a B companion
		Paardekooper et al. 2002	B = β Cephei type ?
WR66 (WN8(h))	3.5-4h	Antokhin et al. 1995	Due to a companion ?
		Rauw et al. 1996	
WR 123 (WN8)	9.8h	Lefèvre et al. 2005	MOST era

Probably the best case in Table 2 is WR 66 (WN8(h)) which has been detected as periodically variable by two independent teams. However, in the case of WR 66 also, there is a companion at 0.″4 that could be responsible for the periodicity. However, this is not the most likely hypothesis. The final conclusion from all these surveys was that ground-based variability studies alone present difficulties to get rid of the atmospheric variations at the necessary low level (0.003 mag) and at the time scales of tens of minutes. Therefore, space-borne measurements were claimed to be much more promising. Indeed, very recently, the MOST satellite discovered the first indubitable case of the presence of a short period in a WR star (the case of WR 123, WN8; Lefèvre et al. 2005 and Lefèvre 2009). The same satellite observed a very stable WR star....WR 111 (WC5; Moffat et al. 2008). The recent discovery (to be confirmed) of the presence of the same periodicity in the P Cygni line profile variations of WR 123 (see Lefèvre 2009) provides the very first plausible proof that the signal at the surface could be propagated outwards by the wind without being completely annihilated.

Conclusion

Spectroscopic and photometric variabilities of O and WR stars are widespread. At least part of the variations are due to the winds that present small- and large-scale structures. The connection between pulsations or magnetic fields and the wind structures are likely but not yet firmly established. With present space-borne facilities, we are certainly on the edge to outline the possible missing link between putative pulsations and observed variations.

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