On the origin of variable structures in the winds of hot luminous stars

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ABSTRACT
Examination of the temporal variability properties of several strong optical recombination lines in a large sample of Galactic Wolf-Rayet stars reveals possible trends, especially in the more homogeneous WC than the diverse WN subtypes, of increasing wind variability with cooler subtypes. This could imply that a serious contender for the driver of the variations is \textit{stochastic, magnetic sub-surface} convection associated with the 170 K partial-ionization zone of iron, which should occupy a deeper and larger zone of greater mass in cooler WR subtypes. This empirical evidence suggests that the heretofore proposed ubiquitous driver of wind variability, radiative instabilities, may not be the only mechanism playing a role in the stochastic multi small-scaled structures seen in the winds of hot luminous stars. In addition to small-scale stochastic behaviour, subsurface convection guided by a \textit{global} magnetic field with localized emerging loops may also be at the origin of the large-scale corotating interaction regions as seen frequently in O stars and occasionally in the winds of their descendant WR stars.

Key words: convection – radiative transfer – stars: evolution – stars: winds, outflows – stars: Wolf-Rayet stars

1 INTRODUCTION
Since the first direct observational discovery of clumping in hot stellar winds (Moffat et al. 1988), we have still not reached a satisfactory understanding of the true physical nature of the clumps. This despite their importance in obtaining the true estimate of the mass-loss rate deviates from the first simplest estimates based on a smooth wind. Clearly, mass-loss rates are crucial for understanding the complete evolutionary history of hot luminous stars (Maeder & Meynet 2000). The problem of mass-loss rates applies whether the clumps are optically thin, in which case the smooth-wind-based mass-loss rates are overestimated by a factor of $\approx 2-5$ (Moffat & Robert 1994), or optically thick in a porous medium, which could lead to the opposite situation (Owocki 2008). Whatever the case, however, it does seem apparent that clumps are a manifestation of turbulent structures created by some kind of driver either in the wind itself and/or external to (i.e. at the base of) the wind. Clumps also likely lead to shocks that emit X-rays as indicated from the simultaneous coincidence of line variations in low- versus high-ionization far-ultraviolet lines in the spectrum of a key Wolf-Rayet (WR) star (Marchenko et al. 2006). On a larger scale but related to clumps in a broad sense are the variable discrete absorption components (DACs) seen in the non-saturated resonant P Cygni absorption edges of UV spectral lines of O stars (e.g. Massa et al. 1995, Kaper et al. 1999). These are related to the corotating interaction regions (CIRs) first seen in the Sun (Mullan 1984) and find their drivers on or near the rotating stellar surface probably in the form of magnetic spots or, less likely (e.g. Henrichs 2012), standing-wave crests from non-radial pulsations (Cranmer & Owocki 1996).

The most accepted explanation for the origin of clumps is via radiative instabilities (Owocki et al. 1988). However, the recent re-
velation that magnetic subsurface convection could be present in hot luminous stars (primarily in OB stars evolving near the main sequence) is certainly a mechanism to take into consideration \cite{Cantiello2009, Cantiello2011}. When one includes the perturbative influence of the partial ionization zone of the iron elements (FeCZ) in the outer interior of the star at a temperature of close to \( T_{\text{FeCZ}} \approx 170 \, kK \), this could lead to acoustic and gravity waves that propagate through the outermost radiative skin \cite{Cantiello2009, Cantiello2011} and could serve as a seed to generate stochastic structures at the base of the wind, which finally lead to the observed wind clumps. This early seed to form clumps at the very base of the wind was in contrast to the random fluctuations necessary to initiate the radiative instabilities which were once believed to start further out in the wind \cite{Runacres2002} despite the observations of clumps in the wind of \( \zeta \) Pup, which begin below this radius \cite{Eversberg1998}. However, more recent work of \cite{Bouret2005, Bouret2008} reveals that UV wind line profiles down to the sonic point can only be properly fit if clumping is included. Furthermore, the improved theoretical work of \cite{Sundqvist2013} shows that photospheric perturbations and stellar limb darkening lead to instabilities starting at \( r \approx 1.1 \, R_* \).

Is there any empirical evidence which might allow one to determine if the subsurface convection zone contributes significantly to the formation of clumps? In this study, we examine in this context, the stochastic variability in the most obvious spectral lines from the winds of stars with the strongest known stable winds, those of the WR stars. WR stars have the distinct advantage of exhibiting strong emission lines even in the optical (where high precision groundbased instruments are also very effective) from the whole wind \cite{Eversberg1998} as opposed to only the column towards the star in UV P Cygni absorption edges, broadened by the Doppler effect of the (optically thin outer) wind’s rapid expansion. In a simple way, one might expect WR stars with very high surface temperatures approaching or above \( T_{\text{FeCZ}} \) not to have significant subsurface convective zones, while cooler WR stars would have deeper, but not too deep, FeCZ layers, where convective driving would be more important, as for the FeCZ in Cepheids.

While \cite{Cantiello2009, Cantiello2011} did not consider the temperature dependence of the FeCZ in W Rand He stars, we see no reason why we cannot extend their ideas for OB stars to classical WR stars, which as massive He-burning stars tend to have (sometimes much) higher surface temperatures than those of OB stars. In the OB-star case of \cite{Cantiello2009} it is acoustic and gravity waves emitted in the convective zone that travel through the radiative layer and reach the surface, thus inducing density and velocity fluctuations. Subsurface convection zones in WR stars \cite{Cantiello2009} have similarities to luminous main-sequence stars \cite{Cantiello2009}, have been explored and are also expected to occur near the iron-opacit peak. While the expectation in models of subsurface convection is for a threshold luminosity with an associated stellar mass, the structure of real WR stars near the stellar surface where the star ends and the wind begins is very poorly known, although some progress has been made \cite{HegerLanger1996, Petrovic2006, Gratien2012}. We therefore prefer to explore the empirical dependence of the FeCZ in WR stars on factors that are more observationally tractable, such as the hydrostatic surface temperature \( T_s \), for which reasonably viable values are available from spectral modelling (see below). When \( T_s \) approaches and surpasses \( T_{\text{FeCZ}} \approx 170 \, kK \), there will be little mass involved in the subsurface convection zone to drive acoustic and gravity waves leading to wind clumping. Conversely, as \( T_s \) falls below 170 kK, the FeCZ will occupy significantly more mass below the stellar hydrostatic surface and thus could be able to drive stronger acoustic and gravity waves, leading to stronger wind clumping. The same driving could also lead to enhanced large-scale wind structures such as CIRs.

On the other hand, one would expect radiative wind instabilities to operate under a wide range of conditions, independent of the stellar surface temperature. This would imply that if only radiative instabilities dominate in the clump production process, then all WR winds should be equally clumped. Alternatively, if subsurface convection plays a role in the clump process, then the hotter stars should show progressively less clumping. The purpose of this paper is to test this. To do so, the basic assumption here is that the line variability in all the stars is from clumps. Indeed, it is essential to compare the same phenomenon in each star. Of course, if other mechanisms contribute to the line variability, this would introduce noise in the results. A case in point is the presence of CIRs, which could in principle also be driven by subsurface convection leading to magnetic fields and bright spots at the footprint of the CIRs. However, as we discuss later, the variability of WR winds is dominated by clump activity in most cases.

2 DATA SOURCE

Fortunately, a uniform source of data to test this already exists in the literature: the set of variable line profiles of 25 northern \cite{St-Louis2009} and 39 southern \cite{Chene2011} Galactic WR stars, in search for candidate CIRs. These include samples of WR stars of all subtypes (and thus surface temperature, which correlates well with the wind temperature or spectral subtype) in both the WN and WC sequences. Basically, the degree of variability was determined from four to five repeated spectra of the same star on several different nights. Of particular importance to our present study is the rms variation across the spectral line relative to, and thus independent of, the local line strength, ending where the line peters out on either side of the line centre, when the S/N becomes too low to be significant. This is labelled as \( \sigma \) in Tables\ref{table1} and \ref{table2} which present all the WR stars available along with several important stellar and wind parameters given mainly from the most recent and up-to-date spectral analysis of Galactic WR stars by \cite{Sander2012} for WC/WO stars and \cite{Hamann2006} for WN stars, respectively. Correlations of the line variability with these parameters will be examined in the next section. In some cases, only upper limits are available for \( \sigma \), some of these were obtained from \cite{Chene2011} and three newly estimated in this paper (WR17, 23, 53). Nevertheless, the great majority of the \( \sigma \) values results from calculations made from the spectra in both papers.

Of course having only four to five spectra per star spread over several different nights does not allow one to easily distinguish between small-scale stochastic and large-scale periodic wind variability. Such a distinction would require considerably more data for each star and goes beyond the scope of this preliminary study. However, from previous work, we can be fairly confident that most WR-star line profile variability (LPV) is in fact dominated by clump action, with only occasional CIR action being detected. For e.g. the study of LPV by \cite{LepineMoffat1999} is based on some 20+ spectra for each of 9 WR stars, only one of which appeared to exhibit CIRs. We therefore assume that the majority of the observed LPV in most WR stars probably arises from clumps.

We separate WR stars into their two main sequences, WN and WC, each with fundamentally different characteristics, but we deal
3 ANALYSIS AND RESULTS

While the subsurface convection theory is expected to lead to a correlation of \( \sigma \) primarily with surface temperature as discussed above, other correlations might also operate which should be examined for the sake of completeness. We do this first for the WC stars, whose properties have been known for some time to be more regular and homogeneous as one advances from hot through cool subtypes than is the case for WN stars. This may be partly due to varying amounts of residual hydrogen in different WN stars in contrast to WC stars, all of which have no hydrogen.

3.1 WC stars

Fig. 1 shows \( \sigma vs. T_\star \) taken from Table 1 which spreads over the range 40-120 K. Here we see a rapid increase of sigma for decreasing \( T_\star \) below 50 K, where all stars are of the coolest subtype, WC9. For the hotter stars, there is a gradual decrease in sigma for increasing \( T_\star \). We test the trend for the hotter stars by carrying out a linear correlation analysis of all non-WC9 stars. The dividing line set by St-Louis et al. (2009) and Chené & St-Louis (2011) between stars selected to be candidates for CIRs and the others showing variability presumably more related to the presence of clumps was arbitrarily set at \( \sigma = 0.05 \). It constitutes at best an indication that the stars with a variability level above this threshold are more likely to be found to have CIRs in their wind, which of course, can only be proven by a detailed spectroscopic time series with a characteristic kinematic behaviour. As a consequence, among all WC stars only the most extreme four WC9 stars would appear to possess CIRs. While this is possible, it seems unlikely that only WC9 stars among WC stars should have CIRs, unless CIRs are also driven by global magnetic subsurface convective processes which may be stronger in WC9 stars, where the FeCZ is deeper and likely contains more driving mass. The possible dividing line between stars with clumps only and those with CIRs plus clumps, while highly uncertain (if such a line even exists at all), should probably be curved to follow the observed distribution more closely, i.e. dropping off at higher \( T_\star \).

The above linear fit reveals a modest but significant correlation \( r = -0.50 \). A t-test reveals that the correlation coefficient deviates significantly from zero at the 93 per cent level. Furthermore, the slope is \(-0.00012(6)\). We have replaced the downward-pointing arrows by their most likely values of half their ordinate values. Taking them in either extreme as actual or zero does not change the results significantly.

We now look at other correlations for \( \sigma \), although no plots are shown here (but see data in the Tables). First, \( \sigma \) also varies with WC spectral subtype (\( sp \)) and wind terminal speed, respectively, much as seen in Fig. 1. This is certainly a consequence of the well-known relatively tight correlation for WC stars between \( sp \) and \( T_\star \), and somewhat noisier correlation between terminal speed and \( T_\star \). We assume that the fundamental relation is between \( \sigma \) and \( T_\star \). The correlation between \( sp \) and \( T_\star \) shows that a hotter wind also means a hotter star.

Next we look at \( \sigma vs. R_\star \), mass-loss rate, luminosity, mass, wind opacity (\( \eta = (M_\odot v_{\infty})/(L_\star/c) \)) and Eddington factor \( L_\star/M_\star \). None of these shows a clear trend as seen in Fig. 1.

Finally we check for any correlation of \( \sigma \) with Galactocentric distance, which is now known to correlate tightly with ambient metallicity \( Z \) (Przybilla et al. 2010) and hence initial metallicity of the star. Neglecting or not the stars with CIRs above the line at \( \sigma = 0.05 \) and allowing for significant dispersion in the distances, a trend clearly emerges among the data. The variability seems to decrease with increasing distance from the Galactic centre. However, any possible trend here might be related to the known fact that late-type WC stars tend to be found more frequently towards the Galactic Centre at higher \( Z \) (van der Hucht 2001), thus making them more variable in the context of subsurface convection (assuming that such a zone actually does exist) affecting the wind, everything else being equal. This is of little consequence in the context of this paper though, since it is ultimately the surface temperature that dominates most clearly.

It could be argued that WC9 stars seem to show peculiar behaviour compared to other subtype WC stars, with systematically higher variability due to more frequent presence of CIRs. However, we lack sufficient information on the presence of CIRs, which in any case may also be more enhanced, as are clumps, in cooler stars if the driving factor (subsurface convection) is ultimately the same for both phenomena.

We conclude here that the only viable global correlation is between \( \sigma \) and temperature, with cooler WC stars being more variable due mainly to clump (possibly with additional CIR) activity in their winds.

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2 These plots for WC and WN stars are all available on request from the authors.

3 Note that the scatter in distance can be considerable, with minimum \( \sigma(r)/r \approx 0.3 \) for \( \sigma(M_\odot/c) = 0.5 \) mag for WR stars.
with increasing $T_\star$, following the envelope trend, is probably more likely. As for the WC stars, we now look at other correlations for $\sigma$ from the WN sample. First, $\sigma$ varies with WN spectral subtype and wind terminal speed, respectively, resembling Fig.2 and is probably also a consequence of the correlations for WN stars, though noisier than for WC stars, between $sp$ and $T_\star$ and between terminal speed and $T_\star$. We assume that the fundamental relation is again between $\sigma$ and $T_\star$, even if it is quite noisy. As for WC stars the correlation between $sp$ and $T_\star$ for WN stars, though noisier, shows that a hotter wind also generally means a hotter star.

Next, we look at $\sigma$ vs. $R_{\infty}$ and mass-loss rate. The former again reflects what is seen in Fig.2 since the radius increases with spectral subclass (although with more noise compared to WC stars). The latter only reveals a possible upper envelope, where stars with the highest $M = dM/dt$ tend to be less variable, while the lower envelope is flat.

We now look for correlations of $\sigma$ with luminosity, mass, wind opacity ($\eta$) and Eddington factor $L_*/M_\star$. All of these show no trend as seen in Fig.2. We also check for any correlation of $\sigma$ with Galactocentric distance. Any possible trend here might be related to the known fact that low-metallicity environments such as the outer Galaxy and the Magellanic Clouds favour WNE among WN stars. In this case, it is clearly impossible to determine a trend or relation between the variability and the distance from the Galactic Centre, which, if any exists, is masked by large dispersion.

### 3.2 WN stars

As for the WC stars, we start in Fig.2 with a plot for WN stars from Table 2 of $\sigma$ vs. $T_\star$, which varies over the range 40-140 kK. This time, however, we do not see a clear correlation as in Fig.1 for the WC stars, rather a relatively large scatter in all values of $T_\star$. Part of this scatter could conceivably be due to the more frequent presence of CIRs in WN stars than in WC stars, thereby enhancing the values of $\sigma$ over what comes from clumps alone. An indication of this comes from the two WN stars with CIRs of known period, WR134 and WR1, which are highlighted, or tight.

The idea might appear to contradict the notion proposed above that clumps and CIRs could be related; however, this link need not be linear or tight.

### Table 1. Physical parameters of the WC stars.

| WR   | Type $^1$ | $\sigma$ $^3$ [10$^2$ %] | $T_\star$ [kK] | $v_\infty$ [km/s] | $R_{\infty}$ [R$_\odot$] | $D_{GC}$ [kpc] | $\log M_*/[M_\odot]$ | $\log L_*/[L_\odot]$ | $\log L_*/M_\star$ | Line $^3$ |
|------|----------|--------------------------|--------------|----------------|-----------------|------------|-----------------|----------------|----------------|-----------|
| 4    | WC5      | $<0.012$                 | 79           | 2528          | 2.37            | 9.9         | -4.68           | 5.3             | 12             | 12.9       | CIV 5016   |
| 5    | WC6      | $<0.012$                 | 79           | 2120          | 2.81            | 9.5         | -4.65           | 5.45            | 14             | 8.3        | CIV 5016   |
| 14   | WC7+     | 0.015                    | 71           | 2194          | 2.98            | 8.3         | -4.75           | 5.3             | 12             | 9.7        | CIV 5016   |
| 15   | WC6      | $<0.012$                 | 79           | 2675          | 3.16            | 8.1         | -4.47           | 5.55            | 16             | 12.5       | CIV 5016   |
| 17   | WC7      | $<0.010$                 | 79           | 2231          | 1.99            | 7.9         | -4.85           | 5.15            | 10             | 11.0       | CIV 5016   |
| 23   | WC6      | $<0.015$                 | 79           | 2342          | 2.98            | 7.7         | -4.57           | 5.5             | 15             | 9.9        | CIV 5016   |
| 33   | WC5      | $<0.013$                 | 79           | 3342          | 2.37            | 8.4         | -4.56           | 5.3             | 12             | 22.5       | CIV 5016   |
| 50   | WC7+OB   | 0.015                    | 71           | 3200          | -               | 6.5         | -               | -               | -              | -         | CIV 5016   |
| 52   | WC4      | $<0.015$                 | 112          | 2765          | 0.96            | 7.2         | -4.71           | 5.12            | 9              | 23.3       | CIV 5016   |
| 55   | WC8d     | $<0.015$                 | 50           | 1800          | 5.00            | 7.0         | -4.94           | 5.15            | 10             | 7.1        | CIV 5016   |
| 57   | WC8      | 0.015                    | 63           | 1787          | 3.75            | 6.8         | -4.84           | 5.3             | 12             | 6.4        | CIV 5016   |
| 77   | WC8+OB   | 0.02                     | -             | 2300          | -               | 3.4         | -               | -               | -              | -         | CIV 5016   |
| 81   | WC9      | 0.055                    | 45           | 1600          | 6.28            | 6.5         | -4.7            | 5.15            | 10             | 11.2       | CIV 5016   |
| 88   | WC9      | 0.065                    | 40           | 1500          | 8.89            | 5.7         | -4.8            | 5.25            | 11             | 6.6        | CIV 5016   |
| 90   | WC7      | 0.009                    | 71           | 2053          | 2.75            | 6.5         | -4.83           | 5.23            | 11             | 8.8        | CIV 5016   |
| 92   | WC9      | 0.055                    | 45           | 1121          | 6.81            | 6.4         | -4.8            | 5.22            | 11             | 5.3        | CIV 5016   |
| 103  | WC9d+    | 0.040                    | 45           | 1190          | 6.21            | 5.8         | -4.83           | 5.14            | 10             | 6.2        | CIV 5016   |
| 106  | WC9d     | 0.065                    | 45           | 1100          | 6.28            | 5.7         | -4.86           | 5.15            | 10             | 5.3        | CIV 4650   |
| 111  | WC5      | $<0.011$                 | 89           | 2398          | 1.99            | 6.5         | -4.67           | 5.35            | 12             | 11.3       | CIV 5016   |
| 119  | WC9d     | 0.030                    | 45           | 1300          | 6.66            | 5.1         | -4.75           | 5.2             | 10             | 7.2        | CIV 4650   |
| 121  | WC9d     | 0.050                    | 45           | 1100          | 6.66            | 6.5         | -4.82           | 5.2             | 10             | 5.1        | CIV 4650   |
| 135  | WC8      | 0.010                    | 63           | 1343          | 3.66            | 7.7         | -4.82           | 5.28            | 11             | 5.2        | CIV 4650   |
| 143  | WC4      | 0.007                     | 117          | -             | 7.8             | -           | -               | -               | -              | -         | CIV 4650   |
| 154  | WC6      | $<0.012$                 | 79           | 2300          | 2.37            | 9.1         | -4.72           | 5.3             | 12             | 10.7       | CIV 5016   |

**Notes:**

1. From van der Hucht (2001),

2. From Sander et al. (2012),

3. From St-Louis et al. (2009) and Chené & St-Louis (2011), with additional editing of the $\sigma$ values.

4. Interpolated values based on spectral subclass.

5. From Sander et al. (2012)

6. From St-Louis et al. (2009) and Chené & St-Louis (2011), with additional editing of the $\sigma$ values.
Finally, we examine if there is a correlation between the line variability ($\sigma$) and the relative hydrogen abundance for the WN stars, $\sigma$(H). No correlation is seen, which weakens our original suspicion that variable H could be a source of the scatter in Fig. 2. Perhaps WN stars have more frequent CIRs of varying strength. However, $\sigma$(H) does not invalidate the hypothesis that variable H renders the WN sequence less homogeneous than the WC sequence.

We conclude here that the only viable correlation is between $\sigma$ and $T_v$, with cooler WN stars being somewhat more variable due to clump and CIR activity in their winds.

### 4 DISCUSSION

According to Cantiello et al. (2009), the strength of the convection zone in normal stars is increased for higher (ambient metallicity) $Z$, lower $T_v$ and higher $L_*$.

Fairly clear trend, namely spectral variability decreases with increasing galactocentric radius. This means that variability increases with increasing $Z$, thus apparently supporting Cantiello et al.'s theory. One must be prudent here though, since increasing (ambient) $Z$ also leads to cooler WC subtypes. While the impact of the convection zone and its capacity to generate stronger acoustic waves and thus stochastic structures in the wind, is metallicity-dependent (Cantiello et al. 2009) one might expect the variability of WN stars to be more $Z$-dependent than they are in reality, since they have not yet produced significant amounts of heavy elements beyond He, that have reached their surfaces. However, WC stars have internally produced significant C (typically $\approx 40\%$) and other heavy elements, although no Fe-peak elements, so they too should be most influenced by ambient metallicity. As for $L_*$ we see no trend among WN stars and a negative trend if at all among WC stars. However, the spread in luminosity for WR stars is not large, so it is probably premature to conclude anything too significant from $L_*$. The increase in line variability (independent of the line in most
cases) with decreasing model surface-temperature $T_*$ is clearer for WC stars than it is for WN stars. Some of the noise in this relation for WN stars could be due to supplementary variability caused by CIRs, which are strong in some WN stars and weak or undetected in others. This seems less of a problem for WC stars, where few if any stars deviate strongly from the mean trend. However, the WC trend is strongly dependent on the significantly higher variability among virtually all WC9 (and some WC8) stars. Could this be due to some peculiarity unique to WC9 stars, which often form dust? The answer to this is likely negative, since the non-dust-forming WC9 stars are just as variable on average as those that form significant dust, indicated by the subtype WC9d. However, we cannot exclude that some other parameters might be playing a role in rendering the WC9 stars to be more variable. Also, additional scatter in all relationships for WN stars may be due to their variable amounts of H [though not obvious in $\sigma$ of H], while WC stars are more homogeneous, all of them entirely lacking in H.

Standard line-driven instability should be weaker in slower, dense, optically thick WR winds (Gayley & Owocki 1995), which appears to be in contrast to what is observed. Moreover, as recently presented by Nazé et al. (2013), the low-noise X-ray light curve from the O4If star $\zeta$ Puppis can be explained by the presence of a very large number ($> 10^5$) of small shocks, probably related to similar numbers of wind clumps (Lépine & Moffat 2008). This observational fact supports the existence of a convective layer as the probable origin of such a huge number of clumps (Cantiello et al. 2009), contrary to the hydrodynamical simulations based on line-driven instabilities of Feldmeier et al. (1997), which predict many fewer X-ray shocks.

Recent work on spectral variability of WC9 (and one WC8) stars carried out by S. Desforges (in prep.), with a much larger sample of spectra than the current studies, seems to show higher values of $\sigma$ for most WC9 stars. This could be a result indeed of CIR activity, which becomes more apparent in a larger sample. However, one would also need to carry out a similar study of all WC (and WN) stars, not just WC8-9 stars before reaching any modified conclusions. We therefore take our homogeneous but limited sample as the best basis for now.

Can the trend of increased line variability with decreasing $T_*$ be understood in terms of the simple analysis of WR wind clumps by Lépine & Moffat (1999)? These authors derive an expression for the relative global line-emission profile variability $\sigma_S/S \propto (R_w/N_x)^{1/2}$, with wind resolving power $R_w = v_e/\bar{\sigma}_x$ ($v_e$ = mean wind expansion velocity in the line-emitting region, $\bar{\sigma}_x$...
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5 CONCLUSIONS

While this study of wind variability and its relation to wind structures is limited entirely to WR stars, where their strong winds make detection easier, we believe that our results may be relevant for all hot, luminous stars, where a subsurface Fe-based convection zone is now believed to be located. However, He-burning WR stars can reach much higher surface temperatures ($T_\star$ up to $\approx 200$ kK) than normal H-burning stars ($T_{\text{eff}}$ up to $\approx 50$ kK), so the effects of subsurface convection near the FeCZ at 170 kK will be better sampled. We note that O stars show no obvious trend of wind filling factor $f$ with surface temperature (e.g. Bouret et al. 2012), although the range in $T_{\text{eff}}$ is small (c. 30-45 kK).

CIRs could also be a result of localized emerging loops in a global magnetic field driven by subsurface convection. More work needs to be done to determine the definitive presence of CIRs in WR stars, by measuring their rotation periodicities and other parameters, such as magnetism, pulsations, etc.

With the aim of supporting the work presented in this article, it would be useful to examine WR internal structure models, in particular with respect to density and temperature profiles in the outer envelope where subsurface convection is expected to occur. This would allow one to have a better idea of the importance of the FeCZ, in terms of mass in particular, in its capacity to generate...
clumps. A literature search shows that such model information is currently not readily available.

We note that values of $T_\star$ are model dependent and could all be systematically in error. In fact, they are likely to be underestimated, given the theoretically higher values of surface temperatures found from internal models of He-rich massive stars (Langer & Henkel 1995). This might explain why in this work we see the line variability starting to rise dramatically at relatively low $T_\star$.

In order to test the claim in this paper that subsurface convection may be playing a significant role in hot-star wind clumps (and CIRs), we need to enlarge the sample of WR stars (and increase the number of spectra per star) in search of line variability, particularly in more of the hotter subtypes, and especially among the very hottest WR subtypes, e.g. WO2 (WR102, WR142) with $T_\star = 200$ kK. Such an effort is in progress.

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