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# The First Determination of the Rotation Rates of Wolf-Rayet Stars

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**Abstract.** The most recent stellar models have shown that the faster a massive star spins, the more its nuclear yields, mass-loss rate and lifetime are different from the standard model. One thus needs to know the rotation rate of massive stars to trace their evolutionary tracks adequately. In Wolf-Rayet (WR) stars, the direct measurement of the rotational velocity is impossible, since their continuum emission is formed in the dense wind that hides the hydrostatic, stellar surface. Here, we present a technique to derive the rotation rates of WR stars from a periodic wind phenomenon, the corotating interaction regions (CIR). For five WR stars, a first estimate of the rotation rates has been deduced from the CIR periods.

**Keywords.** stars: Wolf-Rayet – stars: rotation – stars: winds, outflows

## 1. Introduction

Rotation has a great impact on the structure and the evolution of massive stars, as shown by many articles in these proceedings. It is possible to measure the rotational velocity of an OB star directly from the Doppler broadening of its photospheric absorption lines. However, in the case of Wolf-Rayet (WR) stars, the hydrostatic surface is veiled by a dense wind. Hence, their spectra do not show any classical photospheric absorption lines. That is why no fruitful attempt to determine the rotation rates of WR stars has been made so far.

Nevertheless, it is still possible to derive the rotation rates of WR stars from a periodic wind phenomenon. Indeed, if a stellar spot is present at the surface of a hot and massive star (due to magnetic activity or pulsations), the mass-loss rate increases locally and a large-scale density structure in corotation with the stellar surface is formed in the wind (Cranmer & Owocki 1996). This structure, called Corotating Interaction Region (CIR), is observed in WR stars through flux variations in photometry and large-scale profile changes of broad WR emission lines. Hence, the period found in photometric and spectroscopic variations can be related to the period of rotation of the star. To get the rotational velocity, we multiply this period by the stellar radius (found in the literature).

This type of variability has already been observed in WR 6 (P=3.77 d) and WR 134 (P=2.34 d) (Morel *et al.* 1997, 1999). For each of the stars, a unique period has been found for both the photometric and spectroscopic variability. However, the variability pattern stays coherent only within a certain time range. Because of this epoch-dependency, the period determination is only possible if all the data have been taken contiguously and if this period is smaller than the coherence time.

A blind search for CIR-periods in WR spectra would be pricey. Moreover, not all the WR spectra show large-scale spectral variability. Hence a spectroscopic survey has been made by St-Louis *et al.* (2008, in prep) and Chené & St-Louis (2008, in prep) for all "single" galatic WR stars brighter than the 13$^{\rm th}$ mag., in order to search for large-scale line-profile changes in 5 spectra randomly sparced in time. In the sample, all known binaries have been excluded, since large-scale line-profile variability is already expected from wind-wind collision. From this survey, a list of 10 new CIR-type variable candidates has been established.

Among the candidates are WR 1, WR 55, WR 58, WR 61, WR 67, WR 100, WR 115 and WR 120. A first light-curve has been obtained for all of these stars and spectroscopic

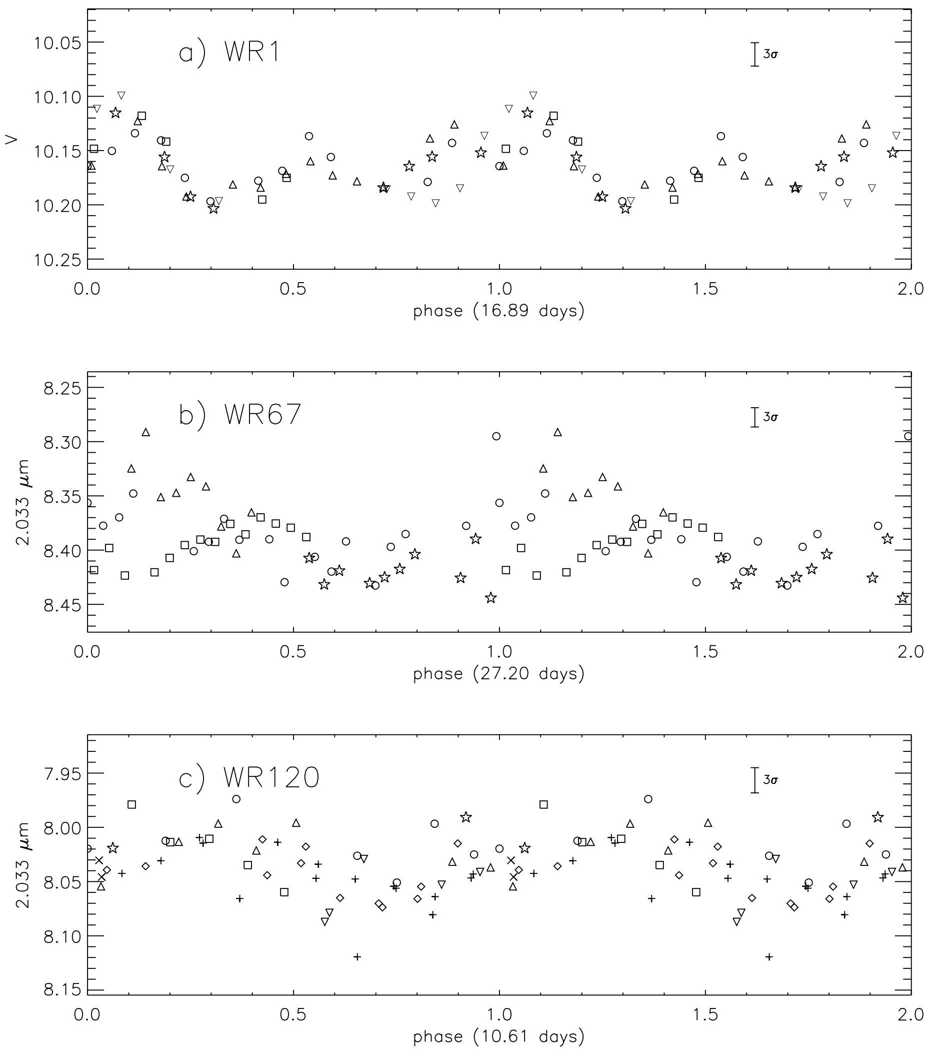


**Figure 1.** Light-curve of a) WR 1, b) WR 67 and c) WR 120 folded with a period of 16.89 $d$, 27.20 $d$ and 10.61 $d$ respectively. Each symbol represent a different cycle; circles for the first cycle, triangles for the second, stars for the third, squares for the fourth, upside down triangles for the fifth, diamonds for the sixth, plus signs for the seventh and x for the eighth. The vertical line indicates the $3\sigma$ error bar.

monitoring for some of them. Here, we present an up-to-date summary of our current results.

## 2. Results

### 2.1. *WR 1*

We monitored WR 1 in broadband $V$ using CCD-imagery at the 0.81m Tenagra Observatory ltd. A search for periods in the light-curve has been done using both PDM and CLEAN techniques and have yielded a unique period of 16.89 $d$ (see Fig. 1.a). Interestingly, the variability pattern does not stay the same during all the campaign. It is coherent during the first 4 cycles, when the light-curve shows three bumps having different amplitudes every cycle. However, the $5^{\mathrm{th}}$ cycle (the curve with upside down triangles) has a different shape. The bump centered near phase 0.8 and the dip centered near phase 1.0 have disappeared. Hence, during the time covered by observations in cycle 5, instead of two bumps, there is only one.

WR 1 has also been observed in spectroscopy at the 1.6m Observatoire du mont Mégantic and the 1.8m Dominion Astrophysical Observatory. In Fig. 3($left$ panel) is the spectroscopic variability of WR 1 shown folded with a 16.89 day period. In this montage of residual spectra, we see that the bulk line-profile variability changes according to the cycle, but still some patterns seem to be recurrent (see bumps and dips traced in dashed and dotted lines, respectively).

### 2.2. *WR 67 and WR 120*

WR 67 and WR 120 have been monitored in a narrowband centered at 2.033 $\mu$ m (a band where no emission lines are present) at the 1.5m CTIO telescope, using the near-infrared camera CPAPIR. The search for period in their light-curve has yielded a period of 27.20 $d$ for WR 67 and 10.61 $d$ for WR 120. In Fig. 1.b and 1.c the two folded light-curves are shown. The period for WR 67 is not completely convincing, since the variability patterns of the different cycles differ between phases 0.0 and 0.3. This could be explained by the epoch-dependency, but new data have to be obtained to confirm this period. WR 120's light-curve has a big scatter over the entire 10.61 $d$-period. This could either be explained by stochastic wind variability or pulsations. WR 120 has been observed also in spectroscopy at the 4m CTIO telescope, but over a time range smaller than the period found in photometry. Nevertheless, the spectroscopic data show variability on a time-scale of days (see the grayscale in the $right$ panel of Fig. 3).

### 2.3. *WR 58 and WR 61*

No photometric period has been found so far for either WR 58 nor WR 61 (also observed with CPAPIR at the 1.5m CTIO). However, in Fig. 2.a and 2.b large-amplitude long-term photometric variability (more than 0.3 mag.) can clearly be seen. Longer time-series are needed to determine if the variability is repetitive.

### 2.4. *The high-scatter light-curves*

No period is found in the light-curve of WR 55, WR 63, WR 100 nor WR 115 (also observed with CPAPIR at the 1.5m CTIO), but the large scatter might indicate an important short time scale variability (from  hours to one day). The actual time sampling frequency is inadequate for such short periods. WR115's light-curve is shown in Fig. 2.c and the grayscale of its spectral residuals in the middle panel of Fig. 3. The

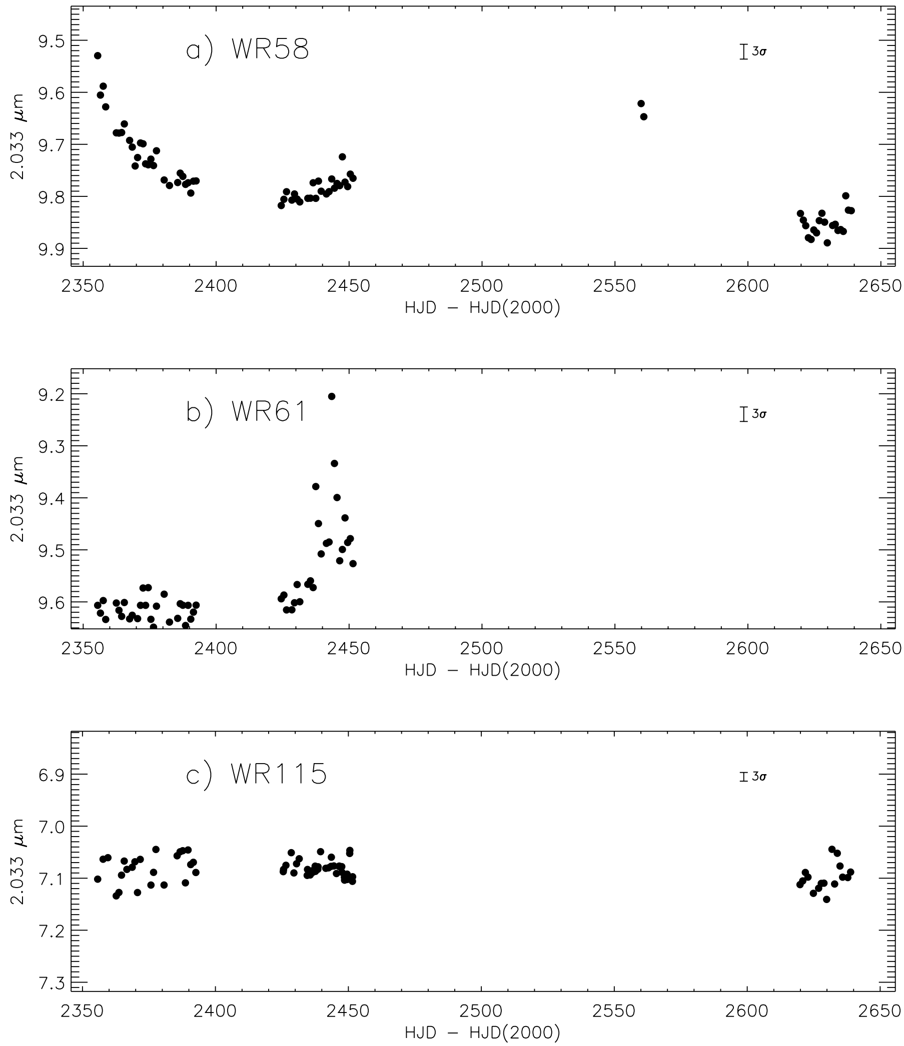


**Figure 2.** Light-curve of a) WR 58, b) WR 61 and c) WR 115. The vertical line indicates the $3\sigma$ error bar.

line-profile variability of WR115 seems to occur on a time-scale of days. Better time sampling is needed to determine the period of variability.

## 3. Conclusion

By taking from the literature the stellar radii of the WR stars for which a CIR periods have been determined (e.g. Hamann *et al.* 1995), a first estimate of the rotation rates of WR stars can be made. All the deduced rotational velocities are presented in Tab. 1. Also, for all the stars in our sample for which no period has been determined, the time-scale of the variability is indicated. All rotational speeds obtained so far are small. This corresponds to the predictions made by Meynet & Maeder. However, it remains to be shown that among our variable candidates, none have variability period. Indeed, all stars

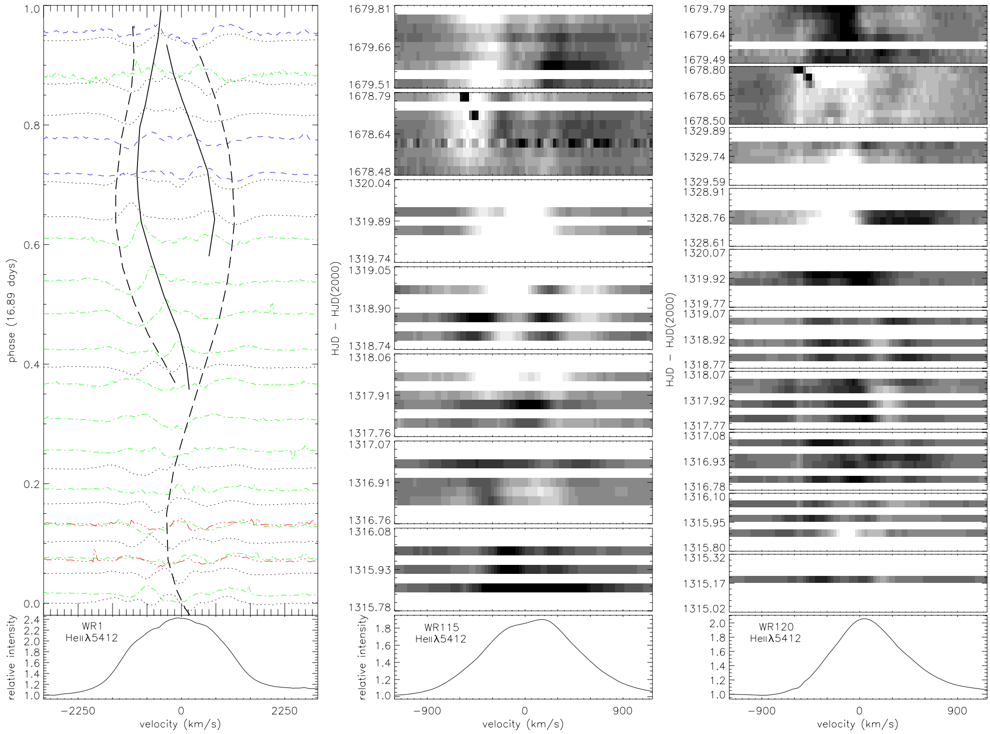


**Figure 3.** *Left* : Spectral residuals of the HeIIλ5412 line of WR 1. The montage is folded with a period of 16.89 *d*. Each line-style corresponds to a cycle; dotted lines for the first cycle, short dashed line for the second, dash dotted line for the third and dash triple-dotted line for the forth. The solid and long dashed lines trace the motion of bumps and dips, respectively. *Middle* and *Right* : Grayscale of the spectral residual of the HeIIλ5412 line of WR 115 and WR 120, respectively. In these grayscale, time increases from the bottom to the top of the y-axis. The brightest regions are bumps and the darkest are dips.

showing variability on time-scales of hours or days in photometry, and also WR 46 (not in the sample) which has periodic photometric and spectroscopic variability with a period of 7 to 8 hours (Veen *et al.* 2002), are all rapid rotator candidates, if we assume that their variability comes from CIRs.

This whole project is based on the assumption that CIRs are attached to the rotating surface of the star. However, in R. Blomme's poster (this volume), the possibility that CIR period could be associated with pulsation periods is discussed. Of course, a lot of theoretical work still has to be done to understand the origin and the characteristics of CIRs. Nevertheless, if all the periods found in photometric and spectroscopic variability of WR stars are purely pulsation periods, we expect them to be proportional to the stellar luminosity. If we assume that the distance to the WR stars is well known, by taking the bolometric magnitudes listed in van der Hucht (2001) ($M_v$=–3.51 for WR 1, $M_v$=–3.52 for WR 6, $M_v$=–3.41 for WR 67, $M_v$=–5.41 for WR 120 and $M_v$=–4.97 for WR 134), we see that it is not the case.

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**Table 1.** Rotation rates of WR stars

| WR | sp. type | period | rot. vel. (km/s)[1] |
|---|---|---|---|
| 1 | WN4 | 16.89 d | 6.5 |
| 6 | WN4 | 3.77 d | 40 |
| 55 | WN7 | few months? | – |
| 58 | WN4/WCE | few months? | – |
| 61 | WN5 | few months? | – |
| 67 | WN4 | 27.20 d | 2 |
| 100 | WN7 | few days? | – |
| 115 | WN6 | few days? | – |
| 120 | WN7 | 10.61 d | 70 |
| 134 | WN6 | 2.34 d | 60 |

*Notes:*
[1] Using stellar radii from Hamann *et al.* (1995).

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## Discussion

Zinnecker: Which rotation rate would you need for a WR-star (surface) so that it would become a progenitor of a long Gamma-Ray Burst?

Chené: According to the current models, a WR star should be rotating faster than 300 km $s^{-1}$. If we take a typical radius for a WR star, this would lead to a rotation period of a few hours.


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