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MEASURING THE ROTATION RATES OF WOLF-RAYET STARS FROM LARGE-SCALE WIND VARIABILITY

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RESUMEN

La velocidad de rotación de una estrella Wolf-Rayet (WR) no puede medirse directamente a partir de líneas fotosféricas de absorción. Sin embargo puede inferirse de la variabilidad a largo plazo del viento estelar. Hemos monitoreado intensamente tres estrellas que presentaban dicha variación. Los períodos de estas estrellas, junto con los ya publicados para WR 6 y WR 134 conducen a una velocidad rotacional para estrellas WR en el rango de 10–60 km s^{-1}.

ABSTRACT

The rotational velocity of Wolf-Rayet (WR) stars cannot be measured directly from "classical" photospheric absorption lines. However, it can be infered from periodic large-scale wind variability. After identifying a list of WR stars presenting large-scale spectral variability, we have monitored 3 of them intensively. The period of these stars, along with the already published periods of WR6 and WR134, lead to a rotational velocity for WR stars in the range of 10–60 km s^{-1}.

Key Words: stars: rotation — stars: winds, outflows — stars: Wolf-Rayet

1. INTRODUCTION

Since 1996, a series of papers published by the Geneva group demonstrated the impact of rotation on the evolutionary tracks of massive stars : rotation oblates stars, introduces a dependence of mass-loss on the azimuthal angle and induces transportation of angular momentum and chemical elements in both directions between the center and the surface. However, in order to appreciate the importance of these effects, one has to know the rotation rates of stars. In the case of OB stars, it is possible to directly measure the rotational velocity from Doppler widening of photospheric absorption lines, assuming a certain angle of the equatorial plane with the line-of-sight. But in the case of Wolf-Rayet (WR) stars, is it possible to measure the rotation velocity when the spectrum is dominated by large emission lines formed in the wind and no "classical" photospheric lines are present?

If the rotational velocity of WR stars cannot be measured directly, it can be inferred from the large-scale variability observed in the winds. In particular, one type of structure that accounts for some of these variations, Co-rotating Interaction Regions (CIRs), are closely linked to the rotation of the star (Cranmer & Owocki 1996). Indeed, CIRs are caused by perturbations at the base of the wind, which in turn could be caused, e.g., by a magnetic field or pulsations. These perturbations propagate through the wind while being carried around by rotation. This generates spiral-like structures in the density distribution that can lead to a characteristic, large-scale, periodic variability pattern in WR-wind emission lines (Dessart & Chesneau 2002). Moreover, CIRs do not suffer from differential rotation but rather enjoy "solid wind" rotation like density waves and therefore provide a direct measurement of the rotation period of the underlying star. Thus after assuming a value for the stellar radius, the period of CIRs directly yields the equatorial rotation velocity of the star, independently of the inclination angle!

2. VARIABILITY OF WR STARS

In the past ten years, large-scale periodic variability of emission-lines has already been observed for two Galactic WR stars, WR6 (P=3.76 days; Morel et al. 1997) and WR134 (P=2.34 days; Morel et al. 1999). These authors proposed that CIRs could explain the variability in both cases. In order to determine if this type of variability is ubiquitous in WR stars, we monitored all Galactic single WR stars brighter than $\sim 13^{th}$ mag using long-slit spectrographs attached to the OMM 1.6 m (Québec) and CTIO 1.5 m (Chile) telescopes. We obtained at least 5 spectra per star and calculated the temporal variance spectra (TVS) for each star, following the formalism of Fullerton et al. (1996). $(\mathrm{TVS})^{1/2}$ is proportional to the variability at each resolution el-

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ement and can be used to indicate the variable parts of different emission lines. Then, using the TVS, we were able to distinguish variable and non-variable spectral lines. Moreover, the TVS can take on different shapes depending on the type of variability, i.e. moving subpeaks, dilution by a variable continuum or global change of the line-profile shape.

By examinating the TVS, we concluded that the spectral lines of 17 stars present no detectable variability with a confidence level of 99%. However, 26 stars present small-scale line-profile variability and 23 stars show large-scale line-profile variability. In Figure 1, we present a histogram showing the different types of variability found in all spectral types. The different types of variability are separated in 3 groups, i.e. large-scale, small-scale and absent variability. As can be seen, some spectral types are exclusively, populated by strongly variable stars. This is the case for WN8 and WC9 type stars. But do they really harbour CIRs?

WN8 stars are known to be strongly variable in spectroscopy and photometry. They are possibly subject to non-radial pulsations due to g-mode (Townsend & MacDonald 2006) or strange-mode pulsations (Dorfi et al. 2006). As for WC9 stars, most of them, if not all, are dust-makers. It has been suggested that all the dust-maker stars are binaries; indeed a well-known mechanism for producing carbon based dust in WR stars implies a wind-wind collision. Considering the above, one can assume that the presence of large-scale variability in the spectrum of these spectral types can be caused by a different phenomenon than CIRs.

Finally, since no WCE stars present any large-scale line-profile variability, the most promising stars remaining for CIRs are WN and WN/WC stars.

3. FIRST ESTIMATION OF THE ROTATION RATES OF WR STARS

From the list of large-scale variable stars established from our survey, we have already monitored intensively some WR stars using photometry and/or spectroscopy with the aim of finding the period. WR1, the clearest new case to date, shows periodic variability in broadband light and emission-line profiles with a period of 16.72 days (Chené et al. 2007). WR120 has a light-curve that shows a small dispersion when folded with a period of 10.49 days (Chené & St-Louis, in preparation) and Antokhin et al. (1995) has published a photometric period of 13.8 days for WR82. Considering all these periods, along with the periods of WR6 and WR134, and depending on the assumed stellar radii, one finds rotational velocities **in the range 10-60 km s^{-1}**.

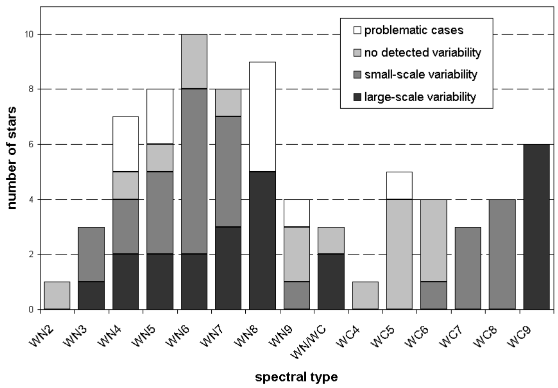

Fig. 1. Histogram showing the number of stars which present large-scale spectral variability (dark-gray), small-scale spectral variability (mid-gray) and no detected variability (light-gray). In white are showed cases for which no conclusion can be made due to the lack of spectra or to the corruption of the spectra by another star in the slit of the spectrograph.

This result is in agreement with the results of Meynet & Maeder (2003) who predicted that WR stars on the He-burning sequence must have slow rotation velocities due to the loss of angular momentum in their strong stellar winds leading up to that stage. However, models of long gamma-ray bursts require the explosion of a fast rotating progenitor, probably of a hot WC-type star (Fryer 2003; MacFadyen 2003) for which current data fail to show much activity at all. Clearly, a great number of other WR stars still should be intensively monitored. With a better determination of the rotation rate of WR stars, we will be able to determine if WR stars are really slow rotators, if their is a difference between H- and He-core burning WRs, and if some stars can indeed be fast rotators in exceptional cases.

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DISCUSSION

S. Owocki - We don't know the nature of the wicked perturber. But if it's a magnetic field, it might not be tied to the star, and if it wanders, then you would not expect phase coherence in the rotation modulation. So your "messy" phase disagreements are perhaps not too surprising.

A. Chené - Yes. And this may explain the "dirty" light curve I have got for WR 120. The epoch dependency of CIRs is the cause of the big challenge we have to determine the periods of the variation. Nevertheless it was possible to obtain stable light curves for WR1, WR6 and WR134. Our hope is that the time of coherence of the variations is most of time greater than the periods of rotation.

A. Maeder - I find most clever the way you proceed to estimate the rotation rate of WR stars. Most of them should be low rotators, otherwise one would have too many GRBs.

A. Chené - Thank you for this comment!

I. Howarth - From your sample, are you able to say anything about the possible relationship between rotation rate and line depolarization (perhaps resulting from a rotationally induced large-scale wind asymmetry)?

A. Chené - No,because I don't have any polarization data for the stars in our sample. All I know is that WR1 is not showing this relation and, due to the small rotation velocity of the others I guess they are not either.

A. Moffat - Just to add to Ian's comment about the correlation between the presence of CIR structures and depolarization in lines: The two stars in your list do show clear CIR structure and deep line depolarization. But WR1 does not. Thus, it's a mixed bag, at least based in small numbers.

A. Chené - You are right. I should have included these results for WR6 and WR134. Note that the periods for these stars are about 2-3 times smaller than the periods of the other stars in the sample.

Virpi, active as ever, showing some support for Goetz's short distance to the Carina region.