Photometric variability of WC9 stars

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ABSTRACT
Do some Wolf-Rayet stars owe their strong winds to something else besides radiation pressure? The answer to this question is still not entirely obvious, especially in certain Wolf-Rayet subclasses, mainly WN8 and WC9. Both of these types of Wolf-Rayet stars are thought to be highly variable, as suggested by observations, possibly due to pulsations. However, only the WN8 stars have so far been vigorously and systematically investigated for variability. We present here the results of a systematic survey during 3 consecutive weeks of 19 Galactic WC9 stars and 1 WC8 star for photometric variability in two optical bands, V and I. Of particular interest are the correlated variations in brightness and colour index in the context of carbon-dust formation, which occurs frequently in WC9 and some WC8 stars. In the most variable case, WR76, we used this information to derive a typical dust grain size of ∼ 0.1 µm. However, most photometric variations occur at surprisingly low levels and in fact almost half of our sample shows no significant variability at all above the instrumental level (σ ∼ 0.005 – 0.01 mag).

Key words: stars: Wolf-Rayet – circumstellar matter – stars: variable: other – stars: carbon – stars: individual (WR76)

1 INTRODUCTION
Population I Wolf-Rayet (WR) stars are the descendants of the most massive stars on the main sequence, namely O stars. They present the signatures of strong, dense winds, in which typical terminal velocities are of order 10^3 km s^{-1}. WR spectra come in two sequences, those with strong lines of helium and nitrogen (WN subtypes) and those with strong lines of helium, carbon and oxygen (WC and WO). WC9 are the coolest stars among population I WC subtypes, with spectroscopic temperatures of order 50000 K at the stellar (hydrostatic) radius, deduced from non-LTE, clumped, line-blanketed models (Dessart et al. 2000; Crowther et al. 2002; Barniske et al. 2006). The particularity of WC9 stars is their frequent very bright luminosity in the infrared that is associated with dust formation (Williams et al. 1987). Some WC9 stars also show strong spectroscopic and photometric variability (Crowther 1997; Eenens & Corral 2003; Kato et al. 2002; Lepine 1996). The brightest WC9 star, WR103, was observed to show periodic behaviour, suggesting a possible binary (Iserstedt & Moffat 1984; Moffat et al. 1986), although later more intense data (Veen et al. 1999) suggested that stellar pulsations are at play, as also confirmed by recent MOST satellite data (Moffat et al. 2008). A few other WC9 stars have been monitored in the optical by Veen (2000), revealing behaviour that reminds one of the all-variable WN8 stars, which typically shows a level of photometric variability of σ ∼ 0.016 to 0.05 mag in the visible (Lamontagne & Moffat 1987; Antokhin et al. 1995; Marchenko et al. 1998; Lefèvre et al. 2003). Photometric variability of other WC9 stars both in the infrared and in the visible can be explained by episodic or periodic dust formation (NIR emission and optical absorption) associated in most cases with binarity (Veen et al. 1998; Williams 1998; Williams & van der Hucht 2000; Williams et al. 2005).

The goal of this study is to provide a systematic, uniform survey of WC9-stars using precision optical photometry in an attempt to answer the questions raised by previous studies, namely: Do all WC9 stars show variability like that of WN8 stars? and Is variability associated with dust formation or with pulsations or both?

2 OBSERVATIONS
We selected a complete sample of 19 WC9 stars and 1 WC8 star in the southern sky from the “VIIth Catalogue of Galactic Wolf-Rayet Stars” and its annex (van der Hucht 2001, 2000) with V-band magnitude from 12 to 16, in order not to go below the minimum practical exposure time of the CCD.
and to stay below a reasonable maximum exposure time of 600 seconds. Observations were made using the Swope 1-meter telescope at Las Campanas (Chile) between UT 2007 June 8 and July 7. We used the direct CCD camera SITe#3 and the two optical bands V and I in order to be sensitive to both magnitude and colour variations, which are of particular interest to constrain the local dust properties. Our field of view is 8.5×10 arcminutes with a pixel size of 0.435". We chose net exposure times such that we obtained a good signal-to-noise ratio (at least ∼300) per observation with one or two observations per clear night for each star. Standard star fields were not observed, since we are only interested in differential photometry.

3 DATA REDUCTION

Extraction of stellar magnitudes from the images was made in the usual way, using nightly flat-field images in each band, nightly bias images and overscan pixels in each image. We then chose to perform aperture photometry on our images, which is more efficient and precise than the alternative point-spread extraction for well-isolated stars in the field. We first interpolated all the images to match a reference frame so that the target star always has the same pixel position. This was done with the ISIS routine interp.csh (Alard 2000). We then chose an adequate number of reference stars (N_ref) for which we measured the instrumental flux F. To do so, we used the IDL function APER with a fixed aperture radius R = 6 pixels (2.610") in I band and R = 8 pixels (3.480") in V band, which correspond to 2×FWHM for typical images, together with a sky annulus of radii [1.5×R, 2.5×R]. The instrumental flux is then computed as

\[ F = \sum_{r<R} P(r) - \pi R^2 \times F_{sky} \]

where \( P(r) \) is the pixel value at radius r and \( F_{sky} \) is the mean flux computed in the sky annulus. The differential magnitude \( \Delta M_i \) of each star in the field is finally given by:

\[ \Delta M_i = -2.5 \log \left( \frac{F_i}{\sum_{j\neq i}^{N_{ref}} F_j} \right) \]

We then sorted the stars in order of variance and chose the \( N_{ref} \) least variable among them to be the new reference stars. We then re-performed the process until it converged. \( N_{ref} \) is chosen in order to minimize the variance of the reference stars and ranges from 10 for a very diffuse field to 50 or more for a crowded field. The photometric precision reached goes from \( \sigma(\Delta M) = 0.005 \) to 0.012 magnitude depending on the quality of the images, essentially determined by the average airmass at which the star could be observed.

4 RESULTS

We found 12 WC9 stars to be variable when compared to reference stars of similar magnitude: WR76, WR48b, WR59, WR75c, WR81, WR88, WR121, WR77t, WR80, WR92, WR96 and WR119 (Fig1 and 2). Their variability ranges from \( \sigma = 0.012 \) to 0.06 mag, the last value referring to the by far most variable star of the sample, WR76. Aside from this star, the level of variability of our sample is quite small (going from \( \sigma = 0.012 \) to 0.02 mag) relative to the "violent" WR103 described by Veen et al. (1999), who confirm a value of \( \sigma(\Delta M) \) of \( \simeq 0.035 \) mag in V band (0.07 mag peak to valley) initially found by Isserstedt & Moffat (1981) and confirmed by Moffat et al. (1986) and Balona et al. (1989). The timescale of the (stochastic) variability of WR76 lies in the range of \( \sim \) a day to several days, like that seen in WR103.

Eight stars were not detected as variables above the instrumental value (Fig3 and 4). Among these stars we estimated the upper bound for \( \sigma_V \) to be around 0.01 for WR106, WR95 and WR65 and around 0.005 for WR53, WR73, WR75a, WR75b and WR117.

5 DUST FORMATION

We searched for a correlation of V vs. (V-I) but only found one for WR76, which is by far the most variable star of our survey. The expected curves for Rayleigh scattering (valid for dust grains smaller than \( \lambda_V/10 \simeq 0.05 \mu\text{m} \)) and grey scattering (valid for dust grains larger than \( \lambda_V \simeq 0.5 \mu\text{m} \)) are shown for comparison. The Rayleigh slope has been computed for Mie scattering with \( Q_{ext}(\lambda, a) \propto \lambda^{-4} \) (see text). Figure 5. V band differential magnitude versus V-I differential colour index for WR76, by far the most variable star of our survey. The expected curves for Rayleigh scattering (valid for dust grains smaller than \( \lambda_V/10 \simeq 0.05 \mu\text{m} \)) and grey scattering (valid for dust grains larger than \( \lambda_V \simeq 0.5 \mu\text{m} \)) are shown for comparison. The Rayleigh slope has been computed for Mie scattering with \( Q_{ext}(\lambda, a) \propto \lambda^{-4} \) (see text).
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Figure 1. Dispersion plots for the fields containing the 12 variable WC9 stars: WR76, WR48b, WR59, WR75c, WR81, WR88, WR121, WR77t, WR80, WR92, WR96 and WR119. These are for the V band except for WR77t, which has been observed only in I band. The reference stars are indicated by triangles and the Wolf-Rayet by a square. On the x-axis is the instrumental magnitude of the stars measured with arbitrary zero point from an image chosen as reference. On the y-axis is the standard deviation in magnitudes of $\Delta M$ with time ($\sigma$).

ity of the star is completely dominated by this star, as seen in Fig 6. For the remaining stars, the correlation is quite poor. In particular, we found variable stars of low amplitude with no dust formation detected (WR75c, WR81, WR88, WR92) together with non variable stars known to produce dust because of their strong infrared excess (WR53, WR73, WR117). This might be at least partly due to the shorter timescale of our variability search compared to that for typical dust ejection.

As some non-dusty WC9 stars show low-level variability, presumably some of that observed from WR76 may also be intrinsic. However, as its high dust formation rate, variable extinction is thought to play a dominant role.

Estimations of the dust formation rates were not available for all our target stars, although the analysis of this correlation does show quite clearly that the production of dust cannot explain the behaviour of all WC9 stars. Like in the strongly variable WC9 star WR103 (Veen et al. 1994; Moffat et al. 2008), we believe that pulsations are likely to play an important role in some cases, sometimes combined with the effects of dust formation.

6 DUST PROPERTIES

It is known that dust in WC9 stars is essentially composed of amorphous carbon grains (Williams et al. 1987; Zubko 1998; Marchenko et al. 2002). We therefore used Mie theory (Bohren & Huffman 1983) and a model of monosize carbon spheres, with optical constants from Zubko et al. (1996), in order to interpret the measured slope of Fig 5 as a dominant size in the dust size distribution. To do so, we calculated the weighted extinction coefficients $Q_{ext}(\lambda, a)$ (function of the wavelength $\lambda$ and the dust sphere radius $a$) as in Marchenko et al. (2004), the weights being given by $W(\lambda) = T(\lambda)F(\lambda)$, where $T(\lambda)$ is the transparency of the corresponding filter (V or I) and $F(\lambda)$ is the energy distribution of WR76 in the optical and the near infrared (Williams et al. 1987). We then used the fact that the extinction, $A(\lambda)$, is...
directly proportional to $Q_{\text{ext}}$. Finally, $A(\lambda)$ is linked to the variations of magnitude that we interpret as due to an increase of the extinction by the dust ($A(\lambda) \propto \Delta \text{Mag}$). The result of our model is shown Fig. 7 for $a$ ranging from 0.0001 to 0.2 $\mu$m. Our estimated dust size, corresponding to a slope of 4.47±0.60, is $a = 0.126\pm0.003$ $\mu$m. This value of $a$ is quite close to the estimation of dust size in WR140 (WC7pd+O5) during its periastron transit in 2001: $a = 0.069\pm0.002$ $\mu$m (Marchenko et al. 2003) but is somewhat lower than other estimations in WR112 (WC9d+OB?) and WR118 (WC9d): $a = 0.4 \sim 1.0$ $\mu$m (Chiar & Tielens 2001; Yudin et al. 2001; Marchenko et al. 2002).

7 CONCLUSIONS
The most surprising result of this study is the large fraction of WC8/9 stars that are not variable above the $\sigma \sim 0.01$ mag level. Even among the 12 that do vary, it is mostly at a relatively modest level, $\sigma \lesssim 0.02$ mag, in contrast to their highly variable WN cousins, the WN8 stars. We see a significant variation in both V and I filters for only one object, WR76, which we ascribe to variable circumstellar dust extinction. We estimated the dominant dust grain size to be close to 0.1 $\mu$m, which is $\sim$ an order of magnitude smaller than estimated in two other WC9d stars.

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Figure 3. Dispersion plots for the fields containing the 7 non-variable WC9 stars WR106, WR95, WR65, WR73, WR75a, WR75b and WR117, and the non-variable WC8 star WR53 as in Fig.4. These are all for the V band.

Figure 4. V and I lightcurves for the 8 non-variable WC9 stars compared with a reference star of approximately the same magnitude in V.

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Table 1. Measured V and I variability compared to typical values for the reference stars. The latter is estimated from the rms mean of the reference stars $\sigma$. 'Slope' is the slope of the (V) vs (V-I) plot (Fig. 1), which was only significant for the most variable star of the survey, WR76.

| Star name | Spectral Type | $\sigma_V$ of WR | $\sigma_I$ of WR | $\sigma_V$ of typical reference star | $\sigma_I$ of typical reference star | Slope |
|-----------|---------------|-----------------|-----------------|-------------------------------------|-------------------------------------|-------|
| WR76      | WC9d          | 0.060           | 0.094           | 0.051                               | 0.006                               | 4.47±0.60 |
| WR48b     | WC9d          | 0.018           | 0.005           | 0.017                               | 0.005                               | -     |
| WR59      | WC9d          | 0.012           | 0.005           | 0.017                               | 0.007                               | -     |
| WR75c     | WC9           | 0.015           | 0.005           | 0.017                               | 0.005                               | -     |
| WR81      | WC9           | 0.016           | 0.010           | 0.021                               | 0.010                               | -     |
| WR88      | WC9           | 0.017           | 0.005           | 0.021                               | 0.006                               | -     |
| WR121     | WC9d          | 0.019           | 0.008           | 0.020                               | 0.009                               | -     |
| WR77t     | WC9d          | -               | -               | 0.017                               | 0.005                               | -     |
| WR80      | WC9d          | 0.012           | 0.006           | 0.011                               | 0.007                               | -     |
| WR92      | WC9           | 0.013           | 0.008           | 0.014                               | 0.007                               | -     |
| WR96      | WC9           | 0.013           | 0.004           | 0.011                               | 0.007                               | -     |
| WR119     | WC9d          | 0.014           | 0.006           | 0.012                               | 0.005                               | -     |
| WR106     | WC9d          | 0.012           | 0.010           | 0.012                               | 0.008                               | -     |
| WR95      | WC9           | 0.009           | 0.007           | 0.012                               | 0.005                               | -     |
| WR65      | WC9           | 0.001           | 0.004           | 0.010                               | 0.007                               | -     |
| WR75a     | WC9           | 0.004           | 0.005           | 0.007                               | 0.007                               | -     |
| WR53      | WC8d          | 0.005           | 0.007           | 0.007                               | 0.006                               | -     |
| WR73      | WC9d          | 0.005           | 0.005           | 0.005                               | 0.005                               | -     |
| WR117     | WC9d          | 0.005           | 0.007           | 0.006                               | 0.008                               | -     |
| WR75b     | WC9           | 0.008           | 0.005           | 0.009                               | 0.005                               | -     |

Figure 6. Our measured level of photometric variability $\sigma(V)$ versus the estimated dust formation rate by Williams et al. (1987). We show the range of values for the instrumental level, which is determined, for each field, by the $\sigma$ of the reference star of closest magnitude to the WC9 star. The dust formation rate estimates are based on infrared photometry. We see that any correlation between the level of variability and the dust formation rate of the WC9 stars is completely dominated by only one star, WR76, combined with a cloud of points at low variability level.

Figure 7. Model prediction of the V vs. (V-I) slope for WR76. We used Mie theory for mono-sized spherical grains plus optical constants for amorphous carbon by Zubko et al. (1996). The best model to reproduce our slope of 4.47 ± 0.60 is a dust size of $a = 0.126 ± 0.003 \mu m$.

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