A comprehensive variability study of the enigmatic WN8 stars: final results

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ABSTRACT

As a conclusion of our all-sky variability survey of the ‘enigmatic’ variable WN8 stars, we have carried out coordinated multisite photometric and spectroscopic observations of WN8 stars in 1989 and 1994–1995. We confirm the leading role of the stellar core in restructuring the whole wind. This emerges as a statistical trend: the higher the level of the continuum (i.e. core) light variations, the higher the variability of the P Cygni edges of the optical emission lines. However, the form of the correlation between the light and profile variations is generally different for each individual star. The high level of activity of WN8 stars may be supported/induced by pulsational instability.

Key words: stars: variables: other – stars: Wolf–Rayet.

1 INTRODUCTION

WN8 stars are the direct evolutionary descendants of massive and luminous Of stars (Maeder 1996; Crowther & Smith 1997). They possess some properties that distinguish them from the general Wolf–Rayet (WR) population. (a) They consistently demonstrate the highest level of omnipresent intrinsic variability (Lamontagne & Moffat 1987; Robert et al. 1989; Antokhin et al. 1995). (b) Their binary frequency is very low (Moffat 1989). Apart from the extremely wide wind-interacting visual binary WR 147 (WN8 + B0.5 V; Williams et al. 1997; Niemela et al. 1997), claims of suspected short-period binarity among WN8 stars have been mainly based on light-curve variations. The best examples are HD 96548 = WR 40, with two prevailing periodicities in light variations, P = 12.3 and 17.5 d, interpreted as binary orbital revolution and axial rotation of the WR component (Matthews & Moffat 1994), and HD 134819 = WR 66, with a clear periodicity of 3.51 h (Antokhin et al. 1995), independently confirmed by Rauw et al. (1996). In general, the search for coherency in radial velocity and light variations has led to controversial results (M assey & Conti 1980; Lamontagne, Moffat & Seggewiss 1983). (c) Some WN8 stars have large distances from the Galactic plane, far exceeding the scale height \( z \) \( \sim \) 60 pc for Galactic WR Population I stars (Moffat & Isserstedt 1980; van der Hucht et al. 1988). (d) WN8 stars avoid stellar clusters and associations. (e) Some WN8 stars have high runaway speeds (Moffat et al. 1997)

Taken together, these five facts have led many authors to a logical conclusion: some (if not all) WN8 stars may be runaway objects after a supernova recoil

We started our systematic survey of WN8 stars in 1989, with more intense follow-up in 1993 (Marchenko et al. 1994; Antokhin et al. 1995), in an attempt to sample adequately the light variations on time-scales of hours–weeks and search for any periodic phenomena which may be attributed to binarity. Here we report our 1994–1995 observations, thus completing our all-sky variability survey of bright, \( m(V) \leq 13 \) mag, WN8 stars. In 1995 we decided to include in
our sample one more star, WR 98, as an example of a possible binary (Niemela 1991) with hybrid WN7/WC7 spectrum and suspected high level of variability. For a first compilation of a list of objects, we started with the spectral subtypes from van der Hucht et al. (1988), being aware that further attempts at reclassification may change the assigned spectral subclass by as much as a subclass (e.g. Smith, Shara & Moffat 1996). This led us to include WR 120 and 148 in our sample, with the latter as a good example of an SB1 system (M archenko et al. 1996).

2 OBSERVATIONS AND DATA REDUCTION

2.1 Photometry

We obtained 10 nights of photometry for WR 40 in 1989 using the 0.5-m telescope of ESO (Chile). The remaining programme stars were observed photometrically for 1 month in 1994 and 2 months in 1995 via two-site broad-band V photometry: at the 0.84-m telescope of the San Pedro M artir (SPM) Observatory, Mexico, and the 0.6-m telescope of the Crimean (Ukraine) Observational Station of GAISH. The extinction coefficients were derived using numerous observations at each site of comparison stars for WR 123, 124, 130 and 148. For the SPM data, we found and applied $k_V = 0.277$ for 1994 June–July, $k_V = 0.258 \pm 0.018$ for 1995 June 21–30, $k_V = 0.141 \pm 0.004$ for 1995 July 1 to August 3 and $k_V = 0.226 \pm 0.017$ for 1995 August 4–18. All the observations from Crimea were reduced into the SPM system by adjusting zero-points calculated from the overlapping data subsets. General information about the observed stars is provided in Table 1, where $\alpha(V)$ refers to $[a_1\alpha(w - c_1) + a_2\alpha(w - c_2)]/(a_1 + a_2)$ for the WR star relative to the non-variable comparison stars ($a_i = 1$ if constant, $a_i = 0$ if variable), or $\sigma(c_2 - c_1)$ for the comparison stars, after allowing for variability of the comparison (if any). The equinox 2000.0 coordinates were measured using the STScI Digitized Sky Survey and its software. The spectral types and narrow-band (continuum) visual magnitude $m$ for WR stars are taken from van der Hucht et al. (1988) and from Smith et al. (1996; values in brackets in our Table 1). The individual observations are given in Tables 2–11. Note that we have not corrected the original data in Tables 2–11 for variability of the comparison stars (see Table 1 for details).

2.2 Spectroscopy

We supplemented our photometry by quasi-simultaneous spectroscopy. We obtained three nights of CASPEC echelle spectroscopy ($\lambda \lambda 5000–6000 \AA$; resolution $\Delta \lambda = 0.2 \AA$ (2 pixels); signal-to-noise ratio S/N $\geq 200$) for WR 40 in 1989 using the 3.6-m telescope of ESO (Chile). Additionally, three stars (WR 123, 124 and 156) were observed spectroscopically from two sites: the 1.6-m telescope of the Observatoire du M ont M égantic, Canada, with attached Cassegrain spectrograph and Thompson 1024 $\times$ 1024 pixel CCD ($\lambda \lambda 3450–5200 \AA$; $\Delta \lambda = 4.9 \AA$ (3 pixels); S/N $\geq 150$ in the stellar continuum for a 1.0–1.5 h exposure), and the 1.8-m telescope of the Dominion A stronomical Observatory, Canada, equipped with a Cassegrain spectrograph and SITe 1024 $\times$ 1024 pixel CCD ($\lambda \lambda 3650–5250 \AA$; $\Delta \lambda = 4.6 \AA$ (3 pixels); typical S/N $\geq 150–250$ in the stellar continuum was reached in 1–2 h. The observations of WR 123, 124 and 156 extend through 1995 May to October – cf. the journals of observation in Tables 12–14. The data reduction was performed using standard IRAF facilities. Comprehensive co-alignment of the spectra using all available prominent interstellar lines, as well as relatively strong night-sky emissions, enables us to reach relatively high (even for the given low spectral resolution) precision in radial velocity: $\alpha(RV) = 3–12 \text{ km s}^{-1}$, depending on the star. All listed heliocentric radial velocities (Tables 12–14) were measured by cross-correlating individual spectra with the mean spec-
the precision of the radial velocities was calculated by cross-correlating the mean spectrum with 3–4 segments, 300–400 Å each, of the individual spectrum and estimating the resulting scatter in RV.

Note: all data were obtained at the European Southern Observatory.

Note: all data were obtained at the San Pedro Martir Observatory.

Note: all data were obtained at the San Pedro Martir Observatory and letter G denotes the data from the Crimean station of the GAISH.

Letter S marks the data from the San Pedro Martir Observatory and letter G denotes the data from the Crimean station of the GAISH.
3 INDIVIDUAL STARS

As a general reference for all programme WNL stars, we point to the study of optical emission-line strengths by Conti & Massey (1989). A summary of all available radio observations is given by Abbott et al. (1986) and Leitherer et al. (1995, 1997); infrared data are provided by Williams, van der Hucht & Thé (1987), Vreux, Andrillat & Biémont (1990), Morris et al. (1996) and Tamblyn et al. (1996).

Attempts to model WNL spectra have been summarized by Crowther, Hillier & Smith (1995a,b), Crowther et al. (1995c) and Hamman, Koesterke & Wessolowski (1995).

3.1 WR 40

This bright star has been observed quite extensively (Matthews & Moffat 1994; Antokhin et al. 1995, and references therein). Multiperiodic character of the variations was suggested by Balona, Egan & Marang (1989). The intricate epoch-depending light variations were decoded using two basic frequencies, \( f_1 = 0.057 \) and \( f_2 = 0.081 \) d\(^{-1} \) along with their harmonics, and interpreted as arising from orbital motion and axial rotation of the WR component (Matthews & Moffat 1994). Based on multiple spectropolarimetric observations, Schulte-Ladbeck (1994) concludes that WR 40 has a variable wind with a time-averaged spherical geometry. Robert (1992) thoroughly discussed microvariability of the He II 5412-Å and He I 5876-Å profiles in WR 40 as caused by rapid, outward propagating wind inhomogeneities.

The time span of our observations (Fig. 2) does not allow us to sample either of the suggested periodicities. We shall discuss this star in detail below, when intercomparing the photometric and spectral variations of WR 40, 123, 124 and 156, with emphasis on the global variations of the wind structure.

3.2 WR 98

This possible long-period binary (\( P = 48.7 \) d, \( e \approx 0 \); Niemela 1991) with hybrid WN7/WC7+? spectrum, is known as a relatively strong non-thermal radio emitter (van der Hucht 1991). All measured C III–C IV and N IV–N V lines move in phase (Niemela 1991). We are not aware of any previous attempt to search for photometric variability of this star. We found no significant periodic variability in our 1995 data.
3.3 WR 105

Recently, this star was reclassified by Smith et al. (1996) as WN9h. Nothing was known previously about the temporal behaviour of this star. There are two possible periodicities in our CLEANed (Roberts, Lehar & Dreher 1987; cf. Antokhin et al. 1995) power spectrum (PS):

\[ f_1 \approx 0.760 \pm 0.002 \text{ d} \]

and

\[ f_2 \approx 1.244 \pm 0.002 \text{ d} \]

They are obviously related by 1-d aliases to the fundamental harmonics

\[ f_3 \approx 0.242 \text{ d} \]

seen in the original PS and corresponding to a feature with peak-to-valley amplitude

\[ A \approx 0.019 \text{ mag.} \]

This is a good example demonstrating that the results of CLEANing cannot be taken at face value. The false-alarm probability (Scargle 1981) is

\[ \sigma = 0.002, \text{ with } 0.001 \text{ and } 0.003. \]

There is no obvious relation of these fluctuations to the binary phase.

Letter S marks the data from the San Pedro M. artar Observatory and letter G denotes the data from the Crimean station of the GAISH.
of the $f_3 \approx 0.242 \, \text{d}^{-1}$ feature is only $p = 0.19$, which is too high a value for $f_3$ to be considered as significant: $p < 0.001$ can be regarded as necessary for a statistically significant periodicity in a relatively small, $N \approx 100$, data set. There are at least two possibilities for diminishing the significance of the $f_3 \approx 0.242 \, \text{d}^{-1}$ frequency: (1) either $f_3$ is not stable during the observations, or (2) $f_3$ is effectively masked by intrinsic 'flicker', i.e., random (or short-lived) intrinsic variations (Fig. 4). The latter seems to be a common cause of variability in practically all observed WN8 stars.

3.4 WR 116 = ST 1 = AS 306

Nothing was known previously about the optical variability of this star. We found one of our comparison stars, c2, to be variable with $f = 0.371 \pm 0.001 \, \text{d}^{-1}$; we removed appropriate least-squares-fitted sine-wave at this frequency from all wr-c2 and c2-c3 data (Fig. 5). In our CLEANed 1994–1995 data we detect periodicity with $f = 0.173 \pm 0.002 \, \text{d}^{-1}$ and $A = 0.043 \, \text{mag}$ (Fig. 5) plus at least two higher harmonics. The false-alarm probability is fairly low: $p < 0.002$.

3.5 WR 120 = Vy 1-3

This previously unobserved star demonstrates the highest level of activity among all WNL stars. The best periodicity derived from our 1995 photometry (Fig. 6) has $f = 0.145 \pm 0.018 \, \text{d}^{-1}$ and $A = 0.043 \, \text{mag}$ and $p = 0.06$, which is not low enough to consider this period as significant. It is
obvious that WR 120 is also variable on a ~ monthly basis, but the data are insufficient for any quantitative implications.

3.6 WR 123 = HD 177230

This star has abundant photometry (Moffat & Shara 1986; Antokhin 1987; Antokhin & Cherepashchuk 1989; van Genderen et al. 1991) with different suggested (multi)periodicities: \( f \approx 0.169, 0.215 \) and \( 0.290 \) d \(^{-1} \) (Antokhin & Cherepashchuk 1989); \( f \approx 0.422 \) d \(^{-1} \) with aliases \( f \approx 0.571 \) and \( 1.428 \) d \(^{-1} \) (Moffat & Shara 1986). Contradicting the results of Moffat & Shara, van Genderen et al. (1991) reported a peculiar light curve with \( f \approx 0.515 \) d \(^{-1} \), two unequal maxima and strong colour variations. Despite the remarkable level of ~ periodic photometric activity, polarimetry of WR 123 does not show any coherent behaviour (St-Louis et al. 1988). However, the polarimetric data are too sparse for adequate sampling of the day-to-week variations.
emerging from the photometry. The search for periodic radial velocity variations puts a stringent limit on any potential change as being due to orbital motion in a binary: \( K \leq 20 \, \text{km s}^{-1} \) (Massey & Conti 1980). Later, with new data, this conclusion was questioned by Lamontagne et al. (1983), who discovered small-amplitude \( K = 17-22 \, \text{km s}^{-1} \) periodic \( f = 0.5677 \, \text{d}^{-1} \), or \( \sim 1\)-d alias at \( f = 0.4351 \, \text{d}^{-1} \) variations in spectral lines, and the star was classified as a \( \text{WR} \, + \, c \) candidate (WR star and compact companion: a neutron star or a black hole).

Our 1994–1995 photometry (Fig. 7) confirms the very high level of activity indicated by all previous observations. Analysis of the original and CLEANed PS helps to pre-select six features at \( f_1 \approx 0.295 \, \text{(A = 0.028)}, f_2 = 0.338 \, \text{(A = 0.026)}, f_3 = 0.578 \, \text{(A = 0.014)}, f_4 = 0.609 \, \text{(A = 0.027)}, f_5 = 0.870 \, \text{(A = 0.017)} \) and \( f_6 = 1.394 \, \text{(A = 0.029)}, \) all with \( \pm 0.002 \, \text{d}^{-1} \). The peak-to-valley amplitudes were evaluated by simultaneous least-squares fitting of six sinusoids with all the \( f_1-f_6 \) frequencies to the original data using the PERDEFT code (Bregger 1989). Within the uncertainties, \( f_3 \) and \( f_5 \) may be interpreted as higher harmonics of \( f_1 \). Note that \( f_5 = 0.295 \) and \( f_3 = 0.578 \) are very close to \( f = 0.290 \, \text{d}^{-1} \) (Antokhin & Cher-epashchuk 1989) and \( f = 0.571 \, \text{d}^{-1} \) (Moffat & Shara 1986).

In an attempt to restore the shape of the light curve, we overplot in Fig. 7 the sum of the fitted \( f_1-f_6 \) frequencies. However, the success of the restoration is limited: about 50 per cent of the power still 'escapes', causing random fluctuations around the modelled light curve. This might be partially explained by taking into account the probable instability of some 'basic' PS components (Marchenko & Moffat 1997). In this star, as well as for WR 124 (two frequencies; see below), we derive false-alarm probabilities
using the estimation of the rms amplitudes after subtraction of the frequencies $f_1$–$f_6$. For the rest of the stars we boldly apply the initial, assumption-free rms amplitudes.

In complete accordance with the photometry, our 1995 spectroscopy reveals the highest level of activity among the three simultaneously observed stars (WR 123, 124 and 156). Contrary to all expectations, a search for periodic variations in radial velocities brings no significant results. All available measurements are plotted in Fig. 8. The scatter of the measured RVs, $\sigma({\text{RV}}) = 17.8$ km s$^{-1}$, allows one to put an upper limit on the RV amplitude arising from hypothetical binary motion of the WR component: $K \leq 25$ km s$^{-1}$, in complete accordance with the value derived by Massey & Conti (1980). We shall discuss causal relationships between photometric and spectral variations in WR 123 later in Section 4.

### 3.7 WR 124 = 209 BAC

This star is surrounded by a spectacular ring (or planetary?) nebula M 1-67, whose status is the subject of a long-lasting debate (cf. Crawford & Barlow 1991; Nota 1995, and references therein). In the heat of the debate about the Population I or PN origin of the nebula, the central star was listed as [WN8]?(SB1) (van der Hucht et al. 1988) – with the remarkably high spatial velocity of $\approx 200$ km s$^{-1}$. Not surprisingly, WR 124 was suspected to be a runaway massive binary with a compact companion and 2.36-d (or 1.74-d alias) orbital period, deduced from the radial velocity and light variations (Moffat, Lamontagne & Seggewiss 1982). A slightly different period of 2.73 d plus significant scatter around the ‘phased’ light curve was found by Moffat & Shara (1986) in broad-band $B$ observations. A series of polarimetric observations over 8 d (St-Louis et al. 1988) showed only incoherent variations.

We found the comparison star c3 to be variable and removed the periodic component with $f = 0.069$ d$^{-1}$ from the wr-c3 and c5-c3 light curves. In so doing, the aperiodic component of the variability of c3 remained unaffected. We note the relatively low level activity of WR 124, both photometric (Fig. 9) and spectral (see below). The cleaned PS reveals two possible periods: $f_1 = 0.225$ and...
f_2 = 0.587 ± 0.002 d^{-1} with A_1 = 0.018, p_1 = 0.0009, and A_2 = 0.016, p_2 = 0.006, respectively. Note that while calculating the values of the false-alarm probabilities and plotting the light curves (Fig. 9), we have pre-whitened each folded light curve from the presence of the other periodicity. The latter frequency is in good agreement with f_0 = 0.58 ± 0.01 d^{-1} found by Moffat et al. (1982). Despite this encouraging result, a search for radial velocity variations provides only weak hints of low-amplitude variability, K = 7–9 km s^{-1} (comparable to K = 13 km s^{-1} reported by Moffat et al. 1982), with possible f_1 = 0.053 or f_2 = 0.084, with ± 0.007 d^{-1}. We do not regard the RV data as a reliable identification of orbital motion in a binary, mainly because the amplitude of the revealed periodicity barely exceeds the averaged accuracy of our measurements, σ(RV) = 5.6 km s^{-1}.

3.8 WR 130 = AS 374

We are not aware of any previous spectroscopy or photometry of this relatively faint star. Our 1994–1995 two-site photometry (Fig. 10) reveals periodicity with f = 0.240 ± 0.002 d^{-1}, A = 0.017, p = 0.020, which cannot be regarded as significant.

3.9 WR 148 = HD 197406

We have included this WN 7 star (WN 8h according to Smith et al. 1996) in our survey as a definite SB1 binary system with possible compact or early-mid B-type companion (Marchenko et al. 1996) as a kind of reference in our quest for short-period binarity among WN 8 stars. We reproduce the 1994–1995 photometry in Fig. 11 along with the...
modelled light curve, folded with the binary period $P = 4.3174$ d. Some overall brightening of the star in 1994–1995 as compared to the model light curve deduced from the 1964–1994 observations (cf. Marchenko et al. 1996) can be seen.

3.10 WR 156

Moffat & Shara (1986) found $f = 0.15$ d with higher-frequency aliases, while Lamontagne et al. (1983) detected no orbital motion in this star. Schulte-Ladbeck (1994) describes the polarization spectrum as flat and featureless.

We found the best frequency $f_1 = 0.064 \pm 0.002$, $A = 0.023$, $p = 0.001$ for (wr-c2) and slightly different $f_1 = 0.069 \pm 0.002$ d$^{-1}$, $A = 0.019$, $p = 0.005$ for (wr-c3) in our data set (Fig. 12). Obviously, the modulation may be caused by the specific variability pattern commencing at HJD 244 9924. There are no periodic RV variations (Fig. 8), despite the low detectability level at 6–9 km s$^{-1}$ and high accuracy of the RV derived from the co-aligned spectra via cross-correlation, $\sigma(RV) = 3.3$ km s$^{-1}$.

4 GENERAL DISCUSSION AND CONCLUSIONS

4.1 Causal relationship(s) between the continuum and spectral variations?

Failing to find any direct relationship between spectral and light variations, we are forced to implement a statistical approach. We simply follow the recipe of Fullerton, Gies & Bolton (1996), calculating the temporal variance spectrum (TVS), with slight modifications. The TVS allows one to estimate the statistical significance of temporal variations across the entire spectrum. At each wavelength (index $j$) we calculate:

$$
TVS_j = \frac{1}{N - 1} \sum_{i=1}^{N} \frac{(S/N)_i}{(S/N)_j} \left( \frac{E_i}{S_i} - \frac{S_i}{S_j} \right)^2 - \sigma^2
$$

where $N$ is the number of spectra; $(S/N)_i$ is the S/N ratio of the $i$th individual, rectified spectrum $S_i$ at a given fixed wavelength $\lambda$; $(S/N)_j$ is the same S/N ratio but for a mean rectified spectrum $S_j$; $E_i$ is the continuum fit to the $i$th raw, non-rectified spectrum; each $E_i$ is normalized, so $E_i = 1.0$. We introduce the value of $\sigma = \sqrt{\sigma_i} \sigma$ (M alanushenko 1988) in an attempt to eliminate any spurious details in the TVS introduced by small errors in the wavelength calibration: $\sigma = 5–10$ km s$^{-1}$ for the stars in our programme. Under favourable circumstances (for example, when pre-rectifying the target spectra by dividing them by the spectra of simultaneously observed standard stars, and thus minimizing the effects of variable atmospheric extinction), we may substitute $E_i/S_i$ for $E_i/S_j$, thus further facilitating the calculations. Additionally, for an assessment of the variability in equivalent width, we use the criterion of Chalabaev & Maillard (1983).

We reproduce in Fig. 13 the mean profiles of ‘representative’ (i.e., practically blend-free) lines of He II 5412 Å and He I 4471 Å (for WR 123, 124 and 156), He I 5876 for WR 40, as the only available He I line in our spectra) along with overplotted values of $(TVS)^{1/2}$, which provide a
possibility for intercomparison of TVS for the spectral features of different intensities. It is immediately clear that the stars can be ranked in accordance with descending level of line profile variability as follows: WR 123, 40 and 124 and, least active, WR 156. This finding is further supported by the test of EW variations, when considering only non-blended and strong spectral features. In WR 123, the variations of He I 4471, 5876 (both the emission and absorption parts of the P Cygni profile) and absorption part of He II 5412 are significant at the 95 per cent (He II) and ≥99 per cent (He I) level. In WR 40, only He I 5876, but not He II 5412, is variable at the ≥99 per cent level, as well as in WR 124, where only the He I 4471, 5876 lines are significantly variable at 95–99 per cent (slightly lower than in WR 40). WR 156 retains the lowest level, with only the He I 5876 line varying at the ≥99 per cent level. As is clear from Fig. 13, the most vulnerable parts are the P Cygni absorptions of He I, followed by less active absorptions of He II. However, the observed variations are incompatible with the expected behaviour of discrete absorption components (cf. Kaper & Henrichs 1994). There is a tight correlation between the photometric and spectral variations: the higher the level of photometric (i.e., almost pure continuum in the broad-band V filter, with only ~5 per cent of line emission for a typical WNL star) variability, the more ‘active’ the spectrum. In other words, the stellar core is triggering (and driving?) the variability, to which the wind is responding. The same conclusion, although based on less direct evidence, was reached by van Genderen, van der Hucht & Steemers (1987).

Can we somehow clarify the nature of the influence of the core on the wind structure? Our limited data do not provide any clear answer. We only note the perfectly synchronized strengthening of the He I and He II absorptions in WR 40 (Fig. 14) when the continuum flux was on the rise (Fig. 2). On the other hand, in WR 123 the gradual synchronized decrease of the He I, He II absorptions (Fig. 15) occurred during erratic light fluctuations (Fig. 7).

The situation concerning short-term (~hours) spectral variations is even more confusing. Contrary to night-to-night variations with synchronized change of He I and He II absorptions, swift 2–4 h changes of He II are not accompanied by any variations in He I lines (Fig. 16)! This desynchronization can take place if (a) the He I absorption is saturated – which is not the case, at least for WR 123, where the short-term variability occurs when the P Cygni absorption of He I 5876 is far from its maximum strength (compare Fig. 15 to Fig. 16), (b) all observed P Cygni variations occur at $v > v_{\infty}$, which would imply $v_{\infty}$ far lower than
usually assigned (Eenens & Williams 1994; Rochowicz & Niedzielski 1995) for these stars, and (c) the last conceivable explanation calls for a non-monotonic velocity law – an assumption which might lead to acceptance of a companion braking the pace of the WR wind acceleration – however, binary behaviour for WR 40 and 123 remains unconﬁrmed.

4.2 What makes the WN8 stars so violent?

Currently we can consider four conceivable agents that could lead to the high level of variability seen in practically all observed WN8 stars.

(1) Binarity. All periodicities emerging from photometry, spectroscopy or polarimetry are completely inconsistent, with strong epoch dependency and hints of multiperiodicities. As the best and most ‘robust’ examples of multiperiodic variability conﬁrmed by numerous independent observations, we mention WR 16 (Gosset et al. 1990; Amtokin et al. 1995) and WR 40 (Matthews & Moffat 1994; Amtokin et al. 1995). The only promising cases (besides the very long-period visual binary WR 147) for a binary-like behaviour are WR 40, 66 and 124 (the last being the weakest).

(2) There are numerous and well-documented indications that WR winds are subjected to localized manifestations of ‘micro’variability, resulting in rapid growth and outward propagation of density enhancements (wind clumping; cf. Moffat 1996). Can such enhancements account for the observed large photometric and spectroscopic variations? The immediate answer is negative: the observed wind structure is affected globally and simultaneously, from \( v_c \) to beyond \( v_c \) (Figs 14–16). If the large variations (up to 0.2 mag) are caused by wind clumping, this should generate polarimetric variations of comparable amplitude. However, the observed polarimetric ﬂuctuations are far smaller: \( \sigma(P) / \sigma(V) \approx 0.05–0.1 \) (Fig. 17; Richardson, Brown & Simmons 1996). This dilemma cannot be resolved by assuming (non-polarized) continuum emission arising from dense blobs: in WR 40 the ﬂux variations show decreasing amplitude toward the infrared (Smith, Lloyd & Walker 1985), in contrast to expected growth due to free–free emission; also, the amplitude of the variations is not enhanced at the Balmer limit (Matthews & Moffat 1994), despite the presence of some hydrogen in the wind of WR 40.

(3) The most comprehensive search for any relationship between the observed variability of WR stars (expressed statistically as the net rms amplitude for a given star: \( \sigma_{net} = \left( \sigma^2(\text{WR} - C_{12}) - \sigma^2(C_2 - C_1) \right)^{0.5} \)) and any of the fundamental parameters, e.g., \( M, L, R, T_{eff}, \) etc., was performed by Robert et al. (1989) with generally negative results, possibly due to a factor of 2 uncertainty in the basic characteristics. The only clear anticorrelation was found between \( \sigma_{net} \) and \( v_c \), tentatively explained as due to differences in propagation time-scales of ‘micro’instabilities (clumps) in the WR wind of a given spectral subgroup: WNL stars as compared to WNE, or WN as compared to WC. We pose the more subtle question: is there any similar dependence between \( \sigma_{net} \) and any of fundamental parameters of the WNL stars? Not surprisingly, we fail to ﬁnd any meaningful correlations between \( \sigma_{net} \) and \( M, L, R, T_{eff}, \) or \( \dot{M} \) for WN8 stars. Even far more accurate \( v_c \) cannot help. However, we do succeed in ﬁnding a correlation between all
available $\sigma_{\text{net}}$ from photometry and polarimetry (Moffat & Shara 1986; Lamontagne & Moffat 1987; van Genderen et al. 1987, 1989; Balona et al. 1989; Robert et al. 1989; Gosset et al. 1990; Antokhin et al. 1995) and the fairly well known relative hydrogen content (Fig. 17) in the stellar wind, as derived by Hamann et al. (1995). The accuracy of the hydrogen content estimation is generally better than 30–50 per cent, when comparing the calculations of Hamann et al. (1995) and Crowther et al. (1995c). The presence of a significant ($H \approx 5$ per cent, by mass) amount of hydrogen may suppress any pulsational instability (Maeder 1985). This may readily explain the general trend seen in Fig. 17. The problem arises when one compares the hydrogen-rich and variable WNL stars to much less variable and practically hydrogen-free WNE/WC stars (Robert et al. 1989): one expects the latter to be violently pulsating in accordance with theoretical predictions. Obviously, the quenching presence of hydrogen must be taken into account while calculating the evolutionary tracks of massive stars, with mass-loss enhanced by vibrational instabilities (Langer et al. 1994).

(4) The most natural source and driver of the variations ($\sim 50$ per cent quasi-periodic, $\sim 50$ per cent stochastic) might be a stellar core generating multimode oscillations, being further transformed by either enhancement or ‘truncation’ of the coherency time? complete evanescence? and transported by the surrounding optically thick WR wind. However, the type and method of transport must be clarified through detailed calculations, which are far beyond the scope of this paper.

A common feature of all the observed light variations is the relatively high scatter around any folded ‘smooth’ light curves, sometimes distorting the regular, periodic variations to a limit of undetectability. This scatter may be caused by short-lived, multimode fluctuations. In WR 123, a growth/damping time for the majority of the short-lived oscillations is $\sim 2–3$ weeks (Marchenko & Moffat 1997), while some of the frequencies (see Section 3.6) remain stable during the observations.

It is established that in WN7–8 stars the wind performance number ($\dot{M} v_{\text{L}}/L$), as well as the wind density, decreases in stars with higher hydrogen content (Crowther et al. 1995c; Willis 1996). An increased wind density might steepen the ionization gradient, thus increasing the efficiency of radiation pressure as a principal driver of the wind. Can this gain completely account for the relatively high wind performance numbers of the WN7–8 stars with low hydrogen content? The answer awaits detailed modelling. Some additional help might come from the pulsational enhancement of mass-loss, if one incorporates the ionization-induced dynamical instability in accordance with Stothers & Chin (1996).

The characteristic time-scales of the photometrical variations of WNL stars, 1–20 d, are reminiscent of the quasi-periodic variations in massive O stars (de Jager 1980), the direct progenitors of WR stars. However, the peak-to-valley amplitudes of the WNL stars, typically 0.05–0.1 mag, are somewhat larger than those observed among the most massive and luminous O stars, 0.02–0.08 mag. Thus the WNL stars might be placed in between OIII–I stars and LBVs (referring to their microvariations) in the maximum light amplitude diagram of van Genderen (1989). Combining very high activity with relatively high luminosity and detectable amount of hydrogen in the stellar envelope, as well as accounting for the suggested direct link between LBV and WNL evolutionary phases (Langer et al. 1994; Crowther et al. 1995c), one is inclined to label WN8 stars the ‘quiescent LBVs’ of the WR population.

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