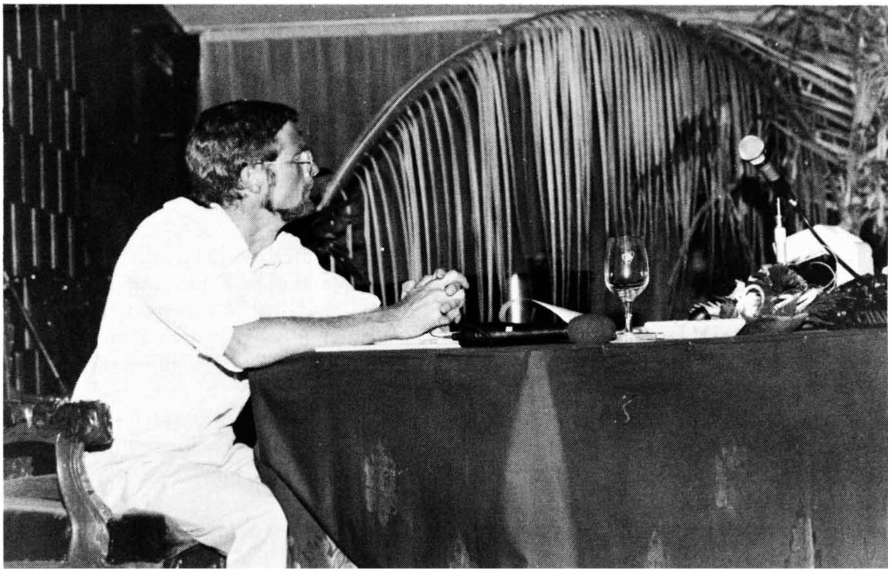
SESSION III. INTRINSIC VARIABILITY – *Chair: Allan J. Willis*



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INTRINSIC VARIABILITY OF WOLF-RAYET STARS FROM AN OBSERVATIONAL POINT OF VIEW

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ABSTRACT. Evidence is mounting that the dominant random component of variability in single WR stars can be explained by one common phenomenon: stochastic formation, propagation and decay of density enhancements in the winds.

1. WR Variability in General

Although it has often been noted that WR stars are basically rather stable at least on long time-scales (e.g. Schmutz 1991), they nevertheless do show varying degrees of variability particularly on short time-scales, in flux and polarization of continuum light and line emission. Only one review on the subject of variability of WR stars has appeared previously (Vreux 1987). The short interval from Vreux's to the present review suggests that the topic of variability is gaining importance in its own right.

In Vreux's (1987) review, the emphasis was on binary- versus pulsation-generated variations. In this review we will discuss mainly intrinsic variability as it relates to whatever observational wind phenomena may prevail. Intrinsic variability due to supernova explosions of WR stars is not considered here. We briefly contrast intrinsic with extrinsic variability, the latter being limited to periodic effects in binaries.

The principal signature of wind variability is the recently discovered presence of systematically propagating emission bumps superimposed on many WR emission lines. These are interpreted as the consequence of outward propagating blobs or waves (Moffat *et al.* 1988) driven by any or a combination of the following:

- intrinsic wind instabilities (Owocki 1990),
- rotation, possibly with a magnetic field (Underhill 1983; Nerney and Suess 1987; Poe *et al.* 1989),
- pulsation, either radial (Maeder 1985) or non-radial (Vreux 1985).

It is hoped that a deep understanding of the variability phenomenon in WR stars will eventually lead to constraints on the stellar parameters themselves which, because of the dense winds, have proved quite evasive.

2. Recent Observations

2.1 Photometry

By far the most photometric work has been done in the optical, where the highest precision is still attainable. Future work may be directed more to the UV (e.g. with the HRS in HST to probe the hot inner parts of the winds) or the IR (to probe the exterior, cooler parts of the wind, e.g. where dust may be forming in some WR stars). Here, we limit the discussion to the optical continuum, although most filter photometry is polluted to varying degrees by the inevitable presence of emission lines, especially in WC stars.

K. A. van der Hucht and B. Hidayat (eds.),
Wolf-Rayet Stars and Interrelations with Other Massive Stars in Galaxies, 109–123.

2.1.1 Binary WR Stars

Lamontagne *et al.* (1991) have shown that essentially all binary WR stars show periodic, phase-dependent light variations, as long as the period is not too long or the orbital inclination and the WR mass-loss rate too small. Apart from the few rare cases of real eclipses of the stars (signature: two light minima per orbital cycle separated by 0.5 in phase for circular orbits), most WR binaries show a single V-shaped dip in their light curves, whose apex occurs when the O star is located behind the WR star, i.e. O-star light is most attenuated by free-electron scattering opacity of the intervening WR wind. The amplitude of the dip varies mainly with $1/a$, $1/v_\infty$, i and $\dot{M}_{WR}$. The successful modelling of the single-dip light curves by Lamontagne *et al.* (1991) shows that at least our gross understanding of the basic structure of WR winds (e.g. spherical symmetry, density-radius law) cannot be too far off base. In fact it gives us some confidence when we come to discuss intrinsic perturbations in the winds.

A special, probably unique case is the WN5 star WR 6 = HD 50896. Over any two-week period this star reveals a coherent 3.766 day periodicity in light (e.g. Drissen *et al.* 1989) but the shape of the light curve changes remarkably on a time scale of months. Is this a precessing binary with a low-mass, compact companion or a single rotating star with some kind of slowly changing wind asymmetry?

2.1.2 Single WR Stars

While there may be some disputed cases, we take to mean "single" those stars for which no duplicity has been explicitly and unambiguously reported either from spectral morphology or periodic behaviour. On the basis of more extensive surveys for photometric variability of WR stars of different spectral subtype (Moffat and Shara 1986; Lamontagne and Moffat 1987; cf. Fig. 1 for sample light curves), one finds that (1) the time scale of the mostly random photometric variations is typically of the order of a day, in contrast to their possible progenitor luminous blue variable (LBV) stage, where the time scale is typically 10 times longer (cf. P Cyg: de Groot 1990), (2) the amplitude of variability tends to be greater for WN than WC stars and increases rapidly towards later subtypes (cf. Fig. 2; e.g. $\sim$ 0.1 mag for WN8, somewhat less for WC9), (3) the variations tend to be independent (or nearly so) of wavelength for true continuum observations.

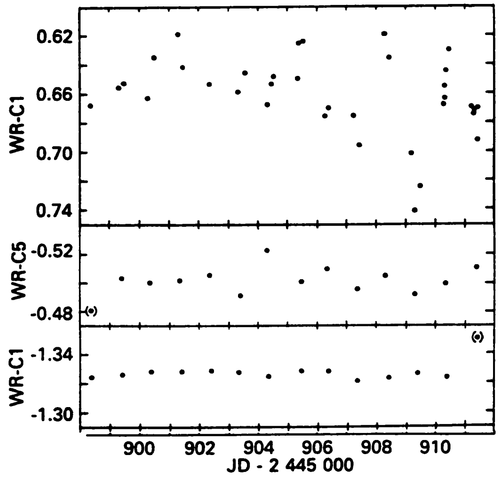

FIGURE 1. Sample B-band photometry of three single WR stars that vary randomly with remarkably different amplitudes: *top* – WR 123 (WN8), σ = 0.030 mag; *centre* – WR 134 (WN6), σ = 0.008 mag; *bottom* – WR 135 (WC8), σ = 0.004 mag (from Moffat and Shara 1986).

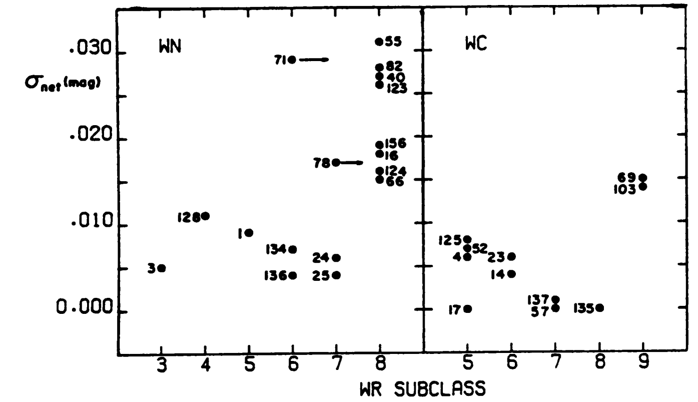

FIGURE 2. Photometric variability of WR stars not known to possess O-type companions, as a function of subclass (Lamontagne and Moffat 1987). The peculiar star WR 6 has been omitted.

Several notable exceptions have emerged from these trends recently. Van Genderen *et al.*'s (1990) intensive photometric monitoring of several WR stars over several nights indicates three stars (WR 46, WR 50 and WR 86) of types WN3p, WC6 + abs and WC7 that vary by 0.03-0.1 mag during intervals of several hours. While WR 50 may be a spectroscopic binary and WR 86 is an equal-magnitude, very close visual binary and thus ambiguous, WR 46 is quite exceptional although its spectrum is peculiar. More intense follow-up of these and other stars is needed, although older studies (e.g. Moffat and Haupt 1974: 7 stars of different subtype; Lamontagne and Moffat 1986: 1 W0 star) found changes below 0.01 mag in ~ 3 hours, more in line with the above global trends. It remains to be seen how typical this large, short-term variability is.

On longer time scales, the WC9 star WR 103 = HD 164270 has twice shown a curious ~ 1 mag dip lasting several weeks, one in 1909, the other in 1980 (Massey *et al.* 1984). Little is known how typical this is (e.g. only WCL stars?), although the WC8 + O binary CV Ser once showed a similar dip (Hjellming and Hiltner 1963) at an orbital phase that does not coincide with the passage of the O star behind the WR star.

In particular, six relatively bright WR stars have enjoyed rather intense photometric monitoring by many different investigators (cf. WR literature compiled for 1980-1990 by van der Hucht 1990): WR 134 = HD 191765 (WN6), WR 136 = HD 192163 (WN6), WR 78 = HD 151932 (WN7), WR 16 = HD 86161 (WN8), WR 40 = HD 96548 (WN8) and WR 103 = HD 164270 (WC9). At first, many of these stars were thought to be low-amplitude, periodic variables and were proposed to have compact companions (cf. Moffat 1982). However, now that much more data have been collected, this is much less certain, with different periods being claimed and periodic signals, if real, generally buried in a much higher level of random noise (cf. Vreux 1985).

The best example is WR 40, which shows large variations and has thus been observed very frequently. In particular, Gosset *et al.* (1989) and Gosset and Vreux (1990) summarize all previous as well as their own attempts to extract periodic sine waves from all data for this star up to the time of publication. In Gosset *et al.* (1989) two global, simultaneous periods are claimed: 2.5d and 6.25d, each with semi-amplitudes of ~ 0.01 mag, compared to the total range of photometric variation of ~ 0.1 mag. This 20% in amplitude translates into ~ 4% power and shows the difficulty of extracting useful information even from long series of data. Figure 3 depicts the plot of all data up to the time of the Gosset *et al.* (1989) publication, phased with the 6.25d period: despite formal statistical tests which strongly support the reality of this period, the figure does little to inspire confidence! Indeed, Gosset and Vreux (1990) revise the 1989 best value of 6.25d to 7d.

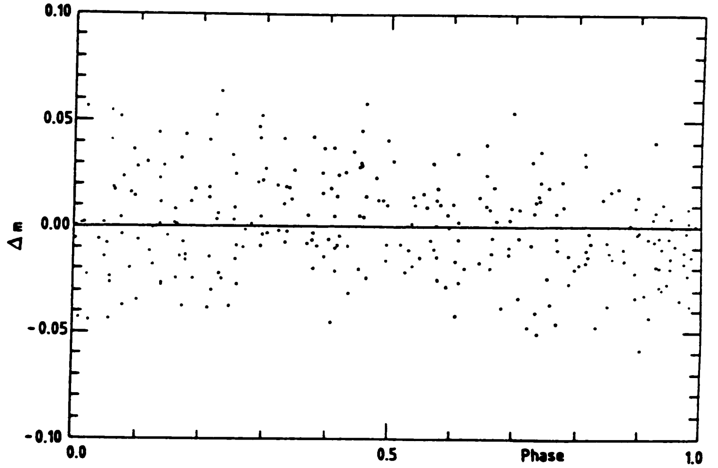

FIGURE 3. A large bank of photometric data for HD 96548 = WR 40 folded in phase with a period of 6.250d (Gosset *et al.* 1989).

2.2 Polarimetry

Although the first serious attempts to look for polarimetric variability in WR stars date to the 1940's (e.g. Hiltner 1950), only recently has there been a great surge in activity. The reason is precision: variations are very small and difficult to detect (< 1%, often < 0.1%) and therefore demand more time per data point than in photometry, something which researchers are less inclined to pursue at first.

2.2.1 Binary WR Stars

The same free electrons in the WR wind that cause a dip in the light curve of WR + O stars when the O star is behind, can scatter O-star light into the line of site. This scattered light will be polarized, depending on the scattering angle; for an ensemble of electrons, the degree of polarization depends on the vectorial sum of all the individual scatterings (cf. Brown *et al.* 1978; Rudy and Kemp 1978). Extensive observations in polarization of WR + O binaries elegantly confirm this simple notion (cf. especially St.-Louis *et al.* 1987; Drissen *et al.* 1987; Robert *et al.* 1989): a double sine-wave in P, θ (or $Q = P\cos 2\theta$, $U = P\sin 2\theta$) per orbital cycle is normally seen in close, circular-orbit binaries, with largest amplitude for $i = 0°$! Note that of all binaries observed, WR + O stars generally show the greatest amplitudes by virtue of their strong ionized winds. Not only are the binary polarization variations independent of wavelength (cf. Luna 1982; Piirola and Linnaluoto 1988), there is also no component of circular polarization (Robert and Moffat 1989), as expected for electron scattering. Furthermore, the amplitude of polarization modulation yields reliable estimates of $\dot{M}_{\rm WR}$ (cf. St.-Louis *et al.* 1988), while derivation of the orbital inclination from the polarization modulation can be used with spectroscopic values of $M\sin^3 i$ to calculate the actual stellar masses. The success of this technique on a broad scale again inspires confidence in our understanding of WR winds.

2.2.2 Single WR Stars

As in continuum photometry, there is a range in the level of polarimetric variability for single WR stars, such that WN stars tend to vary more than WC of similar subclass stars and the late-type, cooler subtypes are more variable (cf. Figs. 4 and 5). In a few cases, there is no detected polarization variability at the instrumental level (~ 0.015% in P for the best observations). Whether this means that there is also zero net intrinsic polarization of the WR star is not clear until one vectorially subtracts off the interstellar (IS) polarization. This turns out to be unreliable in most cases where one tries to determine the interstellar polarization from field stars along the line of site close to

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the WR star: the usual chaotic nature of the ISM is the culprit. However, in one case studied by St.-Louis *et al.* (1987), WR 90 = HD 156385 (WC7), the observed polarization vector of the WR star is identical with the IS polarization at the 0.1% level. This leads to an upper limit of the flattening of the WR wind in this case to $\sim$ 1% (Moffat 1988). Hence, we have at least one case in which it can be asserted that the WR wind is likely to be spherically symmetric (unless one has the fortuitously improbable case of a flattened wind seen pole-on).

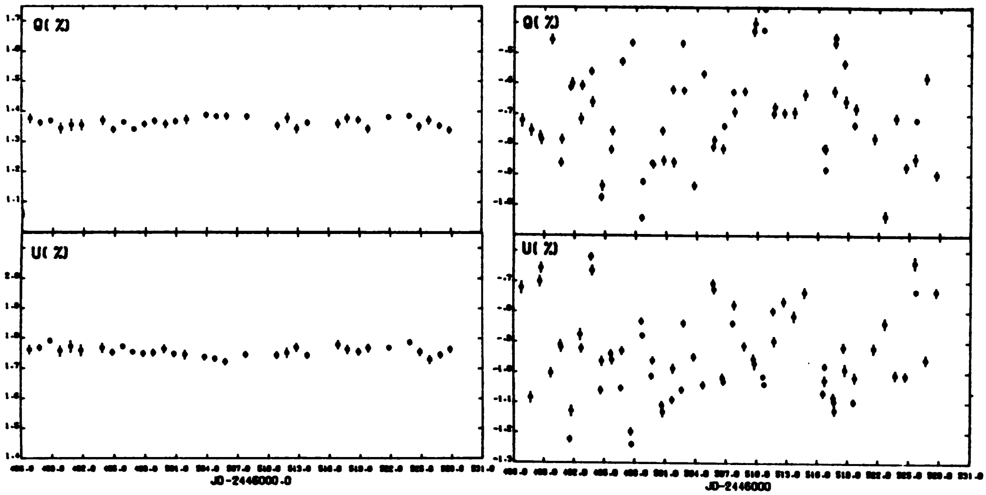

FIGURE 4. Polarization parameters Q and U versus time (separation between ticks is 0.1% and 3 days) for two extremes: *left* – WR 90 (WC7) with σ_P = 0.016%, i.e. essentially instrumental (St.-Louis *et al.* 1987); *right* – WR 40 (WN8) with σ_P = 0.155% (Drissen *et al.* 1987). Note that the scales are identical in both pairs.

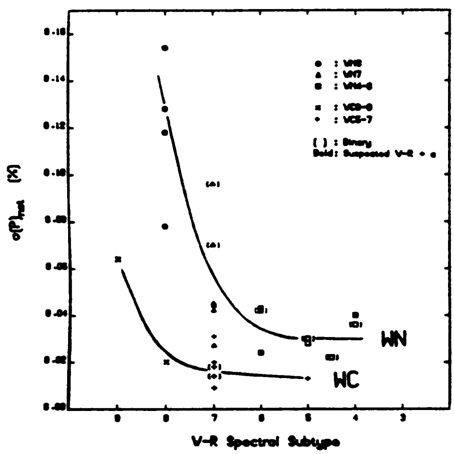

FIGURE 5. Polarization variability of WR stars as a function of subclass (Robert *et al.* 1989).

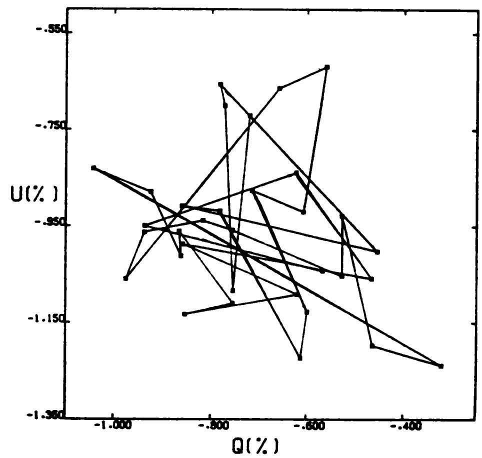

FIGURE 6. Polarimetric variations for the strongly varying WN8 star WR 40 in the Q-U plane (Drissen *et al.* 1987). Note the lack of a preferred plane.

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Another way to subtract off the IS polarization is to decompose the observed continuum polarization at different wavelengths into two distinct components, one wavelength dependent (IS), the other wavelength independent (WR wind scattering). This method has not yet been tried in a systematic way using truly continuum polarization.

For those stars that vary significantly, the variations are clearly dominated by random noise in time (cf. Robert *et al.* 1989). The time scale, as in photometry, is typically about a day, i.e. a factor 10 shorter than seen in polarization variations of potential progenitor LBV's such as P Cyg (Hayes 1985). Furthermore, the general lack of a preferred polarization plane (e.g. a flattened distribution of time-dependent points in the *Q-U* plane; cf. Fig. 6), favours the idea of spatially random events. Finally, the wavelength-independent nature of the variations (Robert and Moffat 1989; Marchenko *et al.* in preparation) implies that electron scattering is responsible.

Taken together, the photometric and polarimetric variability of binary or single WR stars strongly points to the same phenomenon in each. In binaries one appears to understand that phenomenon quite well. In single stars we will first have to look in detail at the spectral variations before concluding what causes their light and polarization variations.

2.2.3 Flux Variability at Other Wavelengths

Attempts have been made to qualify the nature of the flux variability of WR stars in the radio, IR and X-ray regions. Most of these techniques suffer from a lack of sufficient signal-to-noise (S/N).

2.2.3.1 Radio

Hogg (1989) has discussed radio variability in 5 WR stars for which there exist several repeated VLA flux measurements. On a time scale of months to years only one star shows even a hint of significant variability. Compared to the S/N of typically $\sim$ 300 that is routinely obtained in optical data, the S/N here is only $\sim$ 10-20, so it is probably not surprising that variations have not been clearly found in the radio. On the other hand, clear radio variations of over a factor ten have been detected in the unusual, long-period binary WR 140 (Williams *et al.* 1990).

2.2.3.2 Infrared

The only IR monitoring of any significance has been carried out by Williams *et al.* (1987). So far, they have found three WR stars (all WCL) to show large IR eruption-like light curves lasting months. In one case (WR 140), there is a clear correlation with periastron passage in a very long period binary. In the two other stars, binary wind interaction is also suspected. More systematic monitoring at higher S/N is called for.

2.2.3.3 X-rays

Pollock (1987) has found that X-ray fluxes from WR stars tend to be higher in close binaries (probably like O stars: Chlebowski 1989). Especially variable in X-rays (Pollock 1989; Williams *et al.* 1990) is WR 140, as in the IR. Periastron passage enhances the wind collisions between the WR and the O companion such that X-rays emerge later when the optical depth is diminished. Next in variable level is WR 6, which may also be an elliptical orbit binary like WR 140, but of much shorter period and with a neutron star companion (Firmani *et al.* 1980). As noted above however the true nature of this unique system has yet to be revealed. Apart from these two stars, very little significant variability in X-rays has been detected.

2.3 Spectral Variability

While photometry and polarimetry yield spatially unresolved, global, scalar or vectorial sums, respectively, of the light output, spectroscopy offers the advantage of at least partial spatial resolution via the Doppler effect. For example, in a homogeneous, radially expanding wind, monochromatic line radiation will arise in rings concentric with the line joining the star's centre and the observer, the radii of which vary with depth according to the $v(r)$ law of the wind. Any inhomogeneous clumps of wind material propagating radially at velocity $v(r)$ and angle θ relative to the line of site, should then reveal themselves instantaneously in the form of a narrow emission feature at a specific wavelength $\lambda = \lambda_0 + (v(r)\cos\theta)/c$, where λ_0 is the wavelength of the unperturbed line centre. Such a feature could appear in emission from anywhere in the wind, or in absorption if seen close to the line of site to the WR star (P Cyg profile). The study of pure emission lines thus offers the advantage of probing the **global** wind structure, as opposed to the localized column towards the star that one sees in the absorption edge of a P Cyg profile.

Time series of spectra of the brighter WR stars have been carried out with increased frequency recently in both the optical and the UV. The time resolution is typically $\sim$ 15-60 min. Using IUE at high spectral dispersion, the UCL and Colorado groups have published detailed UV variability studies of three WR stars so far: WR 40 (Smith *et al.* 1985), WR 6 (Willis *et al.* 1989) and WR 136 (St.-Louis *et al.* 1989). The last two stars have the most intense data runs. With S/N $\lesssim$50 per 0.1 Å spectral element, these studies are sensitive mainly to the larger variations seen typically in the P Cyg absorption edges, particularly of the strong UV resonance lines. Unlike in O stars (cf. Prinja *et al.* 1990), no narrow absorption-line components (NAC) are seen in these stars. This is surprising, in view of the scaled-up nature of the WR winds compared to O-star winds. However, claims have been made for the presence of NAC's in UV and optical spectra of some WR stars (Koenigsberger 1990). In any case one does tend to see in single WR stars broad UV absorption dips that possibly propagate from intermediate to high negative velocity. The S/N appears to be inadequate to get a definitive handle on this behaviour: the HRS on the HST may be a welcome instrument for scrutiny of this UV phenomenon.

In the optical, an array of WR stars of different subclass is under investigation (Robert in preparation; cf. also Robert *et al.* 1991). So far, only WR 134 (and to a lesser extent WR 136) has been published in any detail (Moffat *et al.* 1988; McCandliss 1988; Underhill *et al.* 1990). All these studies show that (a) the Pickering HeII emission lines behave almost identically, (b) HeII 4686 shows some differences cf. (a), and (c) the NIV 4058 line shows quite different variability. Figures 7 and 8 show an example from Moffat *et al.* (1988); note how the difference spectra allow one best to distinguish different subpeaks by removing the constant background wind emission profile (although with a price: negative artifacts). More details of this technique are given elsewhere (e.g. Robert *et al.* 1991). Suffice it to say here that the overall trend appears to be emerging from the study of different stars that emission subpeaks are accelerating: blue-shifted subpeaks get bluer with time (also applies to absorption dips), while red ones get redder. The intensity of the subpeaks grows and wanes on a time scale of the order of 10 hours.

2.4. Correlation Among Different Modes of Observation

Clearly it would be desirable to monitor some stars intensively and continuously for several days or weeks in as many different simultaneous modes as possible. So far, only a few attempts have been made. Robert and Moffat (1989) used a photo-polarimeter to monitor several stars simultaneously in continuum light, linear and circular polarization. Although truly simultaneous data are rather limited in quantity, it is already reasonably clear that light and linear polarization show little if any correlation, e.g. for WR 40. More recent observations by Drissen *et al.* (in preparation) are being studied to look at this problem in more detail.

Robert *et al.* (1991) are analysing simultaneous photometry (10 nights) and echelle spectroscopy (3 nights) of three WR stars of different subclasses. Again, no clear correlations are evident, although the time scales of the variations are similar, e.g. during one night when the P Cyg absorption components of He I 5876 and He II 5411 in WR 40 increased, the continuum light flux also increased, while other nights of photometric change were not accompanied by an obvious change in absorption edge strength. Clearly this is only the beginning...

2.5 The Peculiar WN8 Subclass

The WN8 subclass is outstanding in its high level of variability compared to all other WR subclasses. Other characteristics make WN8 stars unusual as well (cf. Moffat 1989):

- their spectra reveal narrow, often strong P Cyg profiles even in the optical,
- they avoid star clusters and often show other signs of runaway status,
- they appear to be devoid of O-type binary companions (e.g. in a sample of 9 WN8/9 stars monitored for spectroscopic orbits, **none** showed any orbit that could be attributed to a normal O-type companion, compared to the O stars found to orbit 16 (57%) out of a sample of 28 WN6/7 stars studied for orbital motion).

The mean absolute magnitudes of WN8 stars in the LMC, $< M_v >= -5.6 \pm 0.3$, are only marginally fainter than those of WN6/7 stars, $< M_v >= -6.1 \pm 0.2$ (Moffat 1989), so these two

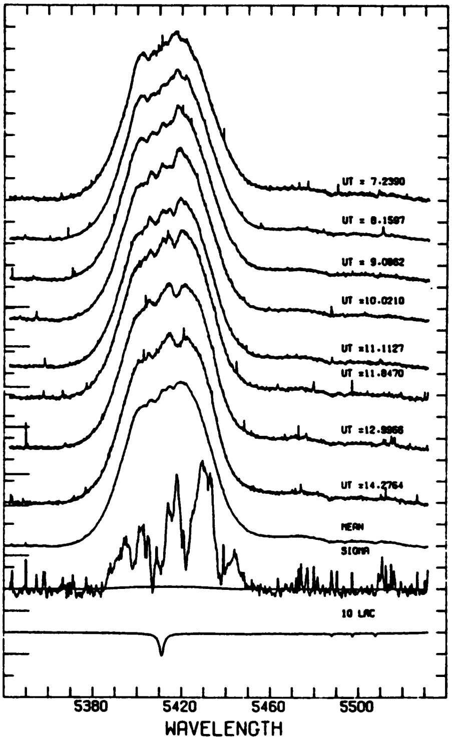

FIGURE 7. Time series of high resolution and high S/N spectra of He II 5411 in WR 134 (Moffat *et al.* 1988).

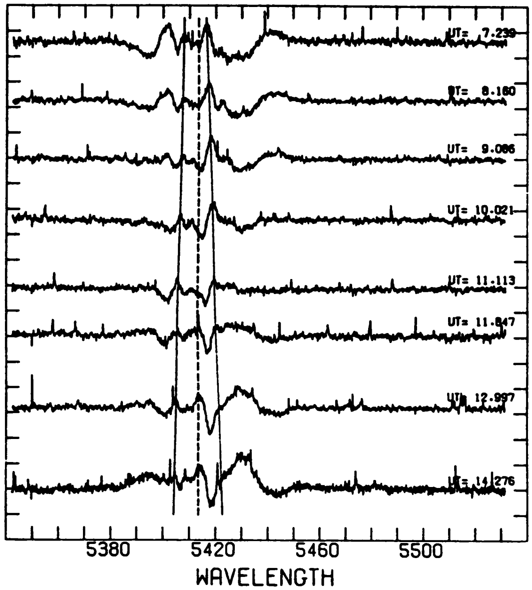

FIGURE 8. Difference from the mean of the spectra in Fig. 7 (Moffat *et al.* 1988). Two sample blobs are traced using solid straight lines as a guide, compared to the line centre (dashed line).

groups appear to have similar masses now as they must have had during their progenitor stage. The remarkable differences between WN8 and WN6/7 stars must then be caused by some other unknown factor, such as their mode of origin (e.g. WN8 stars could be ejected single stars from young clusters or they could be second stage binary WR + c stars, accelerated by a supernova explosion of the original primary, while WN6/7 stars have not suffered either process). These differences must be kept in mind when attempts are made to generalize the variability pattern of the different subtypes.

WC9 stars are also quite variable, but at about half the level of WN8 stars on the average (cf. Fig. 2). Furthermore, there exists at least one known binary among the WC9 stars: WR 70 (WC9 + B0I; Golombek 1983). Thus, even though WC9 stars share some properties with the WN8 stars, such as narrow emission lines, often P Cyg, the similarity stops there. Clearly, WC9 stars deserve further systematic attention.

3. Interpretation

3.1 Source of Variability

As noted in § 1, there are three plausible physical sources of variability in WR stars: pulsation, rotation and intrinsic wind instability. We discuss each of these in turn.

3.1.1 Pulsation

Table 1 gives a comparison of the expected behaviour of WR stars based on theory or as observed in other related (e.g. OB-type) stars, compared to what is actually observed, based on an assessment of the latest data. The general divergence of the two columns suggests that pulsations (radial or non-radial) are not likely to be responsible for explaining the observed variability. This conclusion is supported by other considerations: Noels and Scuflaire (1986) find that g-mode NRP can only be generated in some WR stars of type WNL for a negligeably short interval ($\lesssim$ 5000 yrs); Matthews and Beech (1987) argue against the reality of the NRP periods claimed by Vreux (1985); and Cox and Cahn's (1988) WR models indicate that g-mode NRP are unlikely in any WR star, while fundamental mode RP are possible in low H/He models.

TABLE 1
Comparison of Pulsation Theory with Observed Variability in WR Stars

Property	Pulsation Theory, or [Observed in Other Stars]	Observed
Periods	15-60 min: RP (Maeder 1985) hours: NRP (Vreux 1985)	$\sim$ a day (time scale, mostly non-periodic)
Most Var. Subtype	WNE, WCE: RP (Maeder 1985) (no H)	WNL
Spectral Subpeaks	[b $\rightarrow$ r only: NRP + rotation]	blue $\rightarrow$ blue+ red $\rightarrow$ red+
NAC's	Start at wind base (?)	$(0.5 - 1.0)v_\infty$ in OB star winds
Variability (pol/light)	[$\sim$ 0.01%/0.1 mag for NRP in β Cep (Watson 1983)]	0.5%/0.1 mag

Note: RP = radial pulsation, NRP = non-radial pulsation

3.1.2 Rotation

Most variability of single WR stars is dominated by random processes. Thus it is difficult to believe that any regular pattern associated with rotation can play a significant role in accounting for the observed variations. If there are real periodicities buried in the noise, they may be related to rotation, but they cannot be an important factor. Indeed, it is the rapid, radially expanding winds which dominate WR spectra. A possible exception is the star WR 6, with a 3.766d period which is normally coherent over at least 2 weeks. As noted above, it is uncertain whether this is due to rotation of a single star or the orbit of a low-mass, binary companion.

3.1.3 Intrinsic Wind Instabilities

The random presence of discrete emission subpeaks and P Cyg absorption dips always propagating to higher velocity makes a strong case for stochastic ejection of inhomogeneities or "blobs" of wind material. Note that ejected shells would not give rise to the same effect in the emission lines. We strongly suspect (but cannot prove yet) that the same phenomenon gives rise to the random photometric and polarimetric variations seen in many single WR stars.

We illustrate this blob interpretation for one of the most frequently observed stars, WR 134 (WN6). Figures 7 and 8 have already shown the spectroscopic observations during a typical interval of 7 hours. In Figure 9 we show the radial velocities and strengths of the most obvious subpeaks in these same data, as a function of **time** (the straight lines are only guides to match up the same subpeaks from one spectrum to another). In Figure 10 we present expected radial velocity trajectories of localized density enhancements, assuming: (a) simultaneous radial ejection somewhere into a cone of angle θ relative to the direction towards the observer, who is at $\theta = 0$; the projected velocity will then be $v = v_w \cos\theta$, where v_w is the wind velocity directed radially from the star; (b) a velocity law of the form $v_w(r) = v_\infty(1 - R_*/r)^\beta$, with $\beta = 1$. R_* is the radius of the star, where

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$v_w = 0$. The velocity law can be converted to depend on time instead of radius from the star, r, by a trivial manipulation.

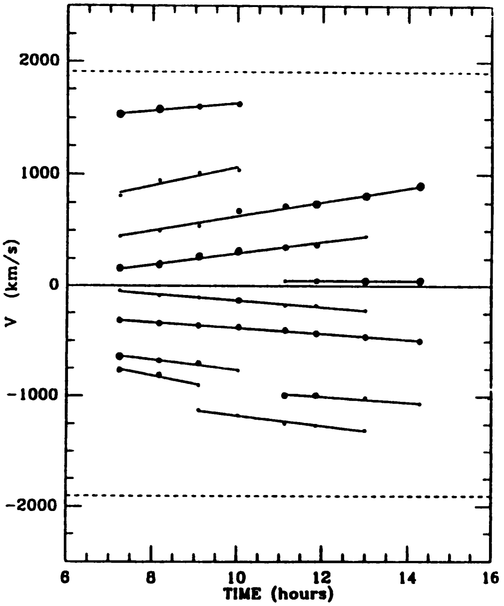

FIGURE 9. Propagation of projected subpeak velocities identified in Fig. 8, with time. Arbitrary straight lines join (assumed) common subpeaks whose strength is proportional to dot size. The terminal velocity from Prinja *et al.* (1990) is indicated by horizontal dashed lines.

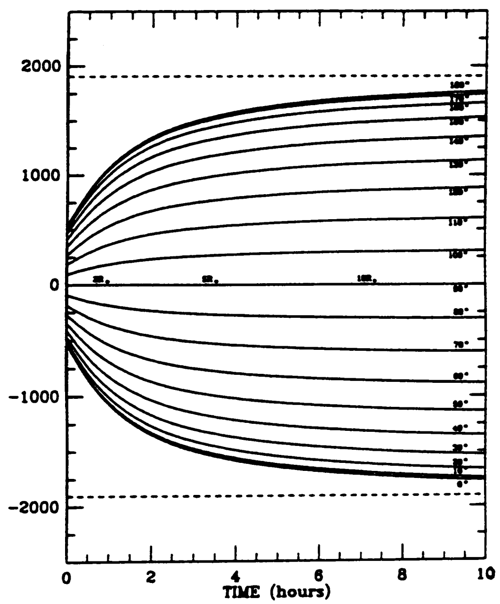

FIGURE 10. Propagation model ($R_* = 7R_\odot$ – St.-Louis *et al.* 1988; $\beta = 1$) to be compared with Fig. 9. Angle of ejection varies from $\theta = 0°$ (towards the observer) to $\theta = 180°$ (away from the observer). Sample true subpeak radii (2, 5 and $10R_\odot$) are indicated on the $\theta = 90°$ line; they apply to all lines of different θ.

Comparison of Figures 9 and 10 must first allow for the trivial fact that the ejection times of individual blobs are random. It is then remarkable that we see no strongly curved trajectories in Figure 9, unlike in Figure 10, especially near the start of the ejection near the star. This may be due to the fact that, like the NAC's in OB-star winds, the growth of blobs does not become significant until beyond $v_w \simeq 0.5v_\infty$, i.e. $r \cong 2R_*$. (In any case the winds of all WR stars except some WNL are generally opaque inside this radius, even in the continuum.) Another interesting factor is that the observed trajectories (Fig. 9) appear to slope differently from the $\beta = 1$ curves at the same angle θ indicate in Figure 10. If the blobs are propagating at the same velocity as the general wind (the similar shape of the dispersion and intensity line profiles in Figure 7 would seem to indicate that this is indeed the case), this can only be understood if in fact β is larger than unity (cf. Robert and Moffat 1990), at least in the intermediate region of the wind that is probed here. Independent evidence for larger β values (i.e. softer winds) beyond the inner part of the wind has been noted previously by Koenigsberger (1991) in the UV spectra of WR stars and Fullerton (1990) in the optical spectra of Of stars. If this turns out to be incorrect, the only alternative is that the (overdense) blobs must be trailing the general wind and thus must be optically thick, in order to have suffered less radiative acceleration. If this effect were extreme, then it would be difficult to account for the fact in Figure 9 that one sees blobs with similar projected velocity distribution as the background wind and none is seen unambiguously in absorption (e.g. mini P Cyg profiles for blobs seen in projection towards the central star).

We give below a summary of the most important properties of the blobs, deduced from inspection of several WR stars of different subclass:

- the ejection process (spatial and temporal) is random,
- they generally provide a few % of the total wind emission,
- slow winds appear less stable (but cool WR have a few large blobs while hot WR have many small blobs at any given time),
- low ionization lines are more variable (since they tend to form further out in the wind, this may mean that blobs grow with time),
- propagation time is typically $\sim$ 10 hours,
- blobs might be useful as potential wind tracers e.g. HeII (Pickering) forms blobs from $R = 2$-$10R_*$ in WR 134,
- stochastic blobs probably account for random variations seen also in light and polarization, due mainly to uncorrelated, wavelength-independent electron-scattering **off** blobs as opposed to line emission **from** blobs,
- blobs are probably driven by (random) wind instabilities,
- many details were predicted before they were detected (Antokhin *et al.* 1988).

4. Concluding Remarks

Can random radial ejection, growth and decay of blobs explain everything (i.e. light curves, polarization variations, spectral variations) seen in single WR stars? Undoubtedly our model is still quite primitive, with many details yet unexplored (e.g. blob sizes, masses, mass frequency...). Qualitatively, the answer to this question is probably affirmative, but a final answer must await a more quantitative study (Robert in preparation).

Even if the emission from the ejected blobs wanes with time, it is not clear that the blobs themselves necessarily dissipate completely. It is conceivable that some (e.g. the largest occasional "super" blobs) survive for a relatively long time, becoming spatially resolved from the central star. Indeed, some WR ring nebulae show knots and filaments which suggest that this might indeed be the case, presuming of course that the clumps were not already there as part of the ISM or previous ejection episodes. The best example may be the ejection-type nebula RCW 58 around the WN8 star WR 40 (Chu 1982) — a familiar star already in this paper — that shows a high level of variability! This nebula exhibits remarkable filaments pointing towards the central star, even close to it (Fig. 11). This cannot be therefore merely a projection effect. The filaments also reveal large abundance excess variations in He and N with position (Rosa and Mathis 1990). Smith *et al.* (1988) find an expansion velocity of $\sim$ 87 km s^{-1} at $r \simeq 2$ kpc from the central star and claim that the clumps originated at most 3×10^4 years ago from a red supergiant progenitor. (But in view of the high luminosity and therefore mass of WN8 stars, and the poor correlation of WR stars with red supergiants — Maeder *et al.* 1980 — it seems more likely that the progenitor was an LBV). This would explain the relatively low expansion velocity compared to the observed WR wind terminal speed of 975 km s^{-1} (Prinja *et al.* 1990). However, one still has to observe the expansion velocities of the filaments very close to the central star, to check for higher velocities more directly from the WR star. Another ring nebula in which inhomogeneous, high-speed, N-rich stellar ejecta are claimed, is RCW 104 around the WN6 star WR 75 = HD 147419 (Goudis *et al.* 1988). Even the SNR Cas A shows fast-moving, N and H-rich knots outside the main optical/radio shell of the SNR (rich in O and S from the explosion itself). These are claimed to be fragments of a WN8 progenitor (Fesen *et al.* 1987).

Future work on the variability of WR stars will undoubtedly profit greatly from the technique of time-resolved, high S/N, high spectral resolution spectro-polarimetry, i.e. obtaining all four wavelength-dependent Stokes' parameters as a function of time. In particular, the degree of depolarization in the **spectra** of individual blobs being expelled at different angles, should allow one to narrow down the geometry. However, to acquire the necessary high quality data ($\lesssim$ 0.5 Å resolution, S/N $\gtrsim$ 3000 in polarimetry (!), and time resolution $\lesssim$ 30 min) will necessitate the use of 8-10 metre class telescopes or larger, even for the brighter WR stars of 7-8 magnitude.

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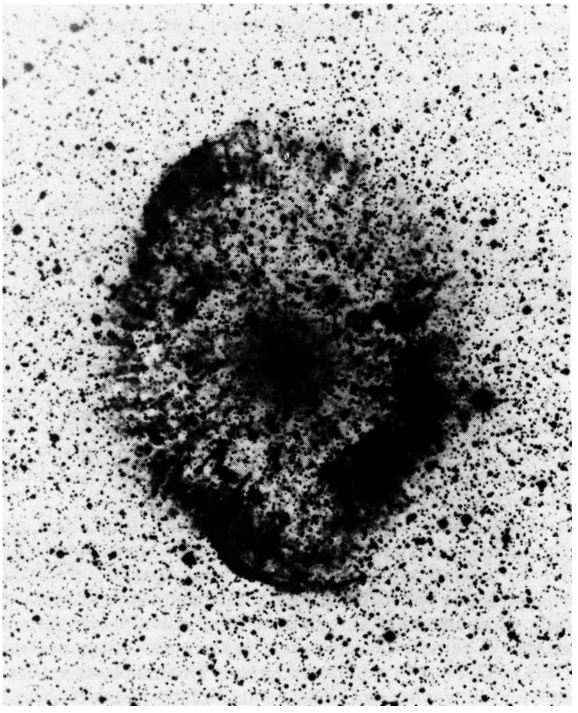

FIGURE 11. Photograph in H_α light of the nebula RCW 58 around the WN8 star HD 96548 = WR 40 (cf. Smith *et al.* 1988).

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DISCUSSION

Conti: (1) Any idea how flattened HD 191765 might be? (2) What fraction of WR stars might have non-spherical winds?
Moffat: (1) Judging from the continuum polarization compared to the maximum depolarized line polarization of HD 191765 of Schmidt (1988), the intrinsic polarization is about 1%. This is like Be stars. (2) According to Schmidt, only 2 out of some dozen or so WR stars show significant depolarization in the lower ionization lines.

Cherepashchuk: Did you try to determine the velocity law from your fine structure spectroscopic observations?
Moffat: Yes. The motion is accelerated but for the detailed interpretation more observations are needed.

Cassinelli: I question your approach in concluding that "rotation is unimportant" based on polarization observations. You isolated intrinsic polarization from interstellar based on variability alone. But as you mentioned only very briefly during your summary, one can also find the intrinsic polarization by observing the change in polarization *vs.* wavelength across a strong emission line. Schmidt and also the Wisconsin group (Schulte-Ladbeck, Taylor, Bjorkman et al.) find from spectropolarimetry that WR polarization properties are often like Be stars, with magnitudes of about 1%. Based on the information we have thus far, I certainly do not think we should conclude that rotation is not important.
Moffat: Only a minority of WR stars show such a depolarization across their emission lines. Indeed, some WR stars (for which the interstellar polarization can be reliably estimated from field stars) show close to zero net-intrinsic polarization.

Koenigsberger: I do not see how you can rule out the existence of radial pulsations in WNE stars. These winds are so dense that the periodic oscillations can not be reflected in the observations.
Moffat: As Owocki points out (see next review talk), any perturbation near the wind base becomes significantly amplified later when it propagates outward with the wind.

Underhill: Recently, Harmanec has interpreted the moving absorption dips in lines of OB stars as due to a rotating spokelike structure rather than as due to NRP. It seems possible that the sets of changing subpeaks (blobs) on emission lines could be interpreted as concentrations of radiating plasma in a set of ever changing rotating filaments in the central hole of a possible disk. It seems significant that the subpeaks are chiefly seen in the velocity range from $-1/2v_\infty$ to $+1/2v_\infty$. If they were freely moving blobs, why do we not see any between $1/2 - 1v_\infty$?
Moffat: But the emission peaks on pure emission-line WR profiles show clear trends of outward acceleration (blue ones get bluer, red get redder). This is not expected from rotation filaments. The subpeaks are seen with similar distribution as the background wind in velocity space, *i.e.* we do see them between 0.5 and $1.0v_\infty$ but fewer in number than between $\pm0.5v_\infty$.

de Groot: Quite apart from questions of interpretation, if one is looking for interrelations with other massive stars, let me point out that very much the same variations you reported for the latest WN stars are also present in P Cyg: similar brightness variations with somewhat larger amplitude again, similar polarimetric varations as you showed, and similar variations in the optical spectrum.
Moffat: [Due to some limitations, a viewgraph of P Cygni light variations by de Groot (1990) was not shown during the talk. This was rectified after this question.]

Sreenivasan: If the star is rotating and if there is evidence for a flattened structure, such a structure would be rotating very slowly (due to angular momentum loss from the star as well as the size of the flattened structure's radius). You are also not observing a homogeneous structure around a star and one would not see any strong correlation with rotation. Further, if non-radial pulsation is present one usually finds many non-radial modes simultaneously excited in evolved stars and again it would be hard to see specific periodicity. So, you would in fact see what you described, although the converse is not necessarily valid.
Moffat: If rotation of the central core does play a role in WR intrinsic variations, there must be some inhomeogeneity associated with it (*e.g.* magnetic loops, spots, non-radial pulsation). These should eventually propagate outward to the visible part of the wind where some trace of periodicity should be observable. There is no compelling case in which one observes this to happen except for HD 50896, which may be a binary in any case.

Maeder: One cannot rule out pulsations in WR stars. The optically thick wind is unable to respond to the short periods of the interior. Only if one could see deep enough in the winds, one could infirm or confirm the existence of pulsations.
Moffat: But as Owocki points out, a small perturbation deep in the wind should become significantly amplified as it propagates outward.

Owocki: (1) I did not understand your distinction between optically thick *vs.* thin blobs moving slower than *vs.* as fast as wind. In simulations we see very dense structures moving at near v_{wind}. (2) In OB NAC, both the repetition and acceleration times seem to be related to the $vsini$, implying rotation is playing some role.
Moffat: (1) If blobs are truely density enhancements, being optically thick means that they will not "see" the whole radiation field and will be less accelerated than thinner parts of the (ambient) wind. (2) Perhaps!

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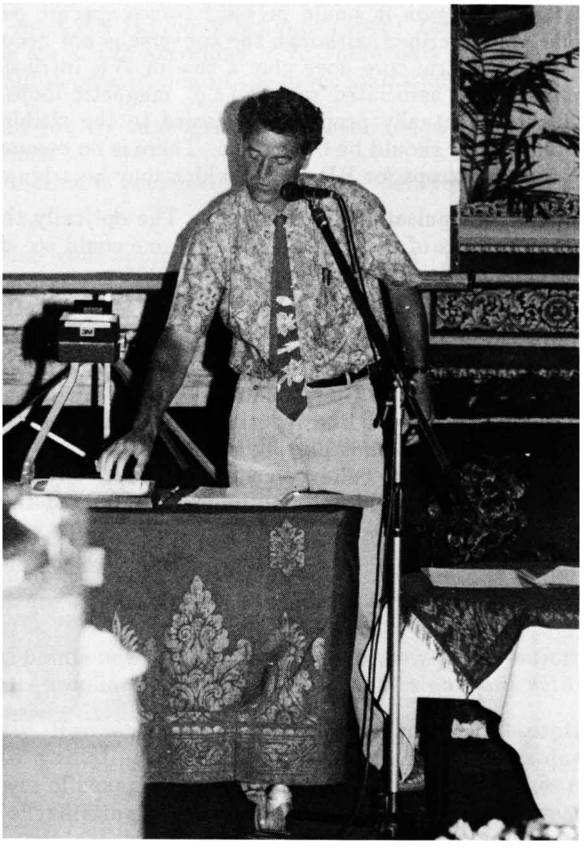

Tony Moffat