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Intensive photometry of southern Wolf–Rayet stars

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Summary. We present results of an intensive photometric campaign on 17 of the brightest southern Wolf–Rayet stars. We report the detection of multi-periodicity in two stars: HD 50896 and HD 96548. It is likely that these periodicities are not coherent but are manifestations of the quasi-periodic variations seen in a few WR stars. A good example of these variations is given by HD 86161. A new eclipsing binary, HD 92740 has been discovered; other stars show periodic variations which can be explained by phase-dependent scattering of the secondary light as it traverses the Wolf–Rayet wind. An important conclusion of this study is that not a single example was found of short-period variations which can be attributed to pulsation.

1 Introduction

Many Wolf–Rayet stars are variable in light with a time-scale of a few days and amplitudes of a few per cent. Except for known binary systems, strict periodicity has not been firmly established and the cause of variation is not understood. Possible mechanisms include the orbital effect of a compact companion, rotational modulation or non-radial pulsation.

The definitive detection of a compact companion would be an important confirmation of some evolutionary scenarios for WR stars. At present, the WN5 star HD 50896, shows the best observational evidence for a compact companion (Firmani *et al.* 1980), though other candidates have been proposed (Moffat 1983). This star has a complex light curve with a period of about 3.76 d. If the presence of a compact companion is common in WR stars, then one might expect to observe similar light curves for other stars. The existing observations are not sufficient to test this point.

Models of WR stars indicate that the fundamental radial mode could be excited due to nuclear-burning instabilities (Maeder 1984; Cox & Cahn 1988). The expected period is about 1 or 2 hr. Non-radial modes, which have longer periods, have been found to be generally stable. Since the photosphere is almost completely obscured by the dense stellar wind, there is some doubt whether pulsation, if it exists, can be detected unless it affects the wind dynamics. The possibility of radial or non-radial pulsations in WR stars has been advocated in certain objects. The strongest cases are perhaps those of HD 192163 (Vreux, Andrillat & Gosset 1985) and HD 86161 (Manfroid, Gosset & Vreux 1987). The existing photometry is insufficient and the time coverage too poor for a convincing case.

For these reasons, we embarked on an intensive program of Strömgren-b and Johnson-B photometry for 17 of the brightest southern WR stars. Observations were made over a continuous four-week period in 1988 January, a continuous seven-week period in 1988 March/April and a further two-week period in 1988 June. For HD 50896 we have accumulated intensive observations over three seasons. This is by far the most intensive coverage ever made for these objects. Coherent periods in the range 1 hr to 2 weeks should easily be detectable provided the amplitudes are larger than a few millimagnitudes. This should be sufficient for a definitive answer to the question of pulsation in these stars.

2 Observations and reductions

All observations were made using the Volks photometer attached to the 0.5-m reflector at the Sutherland site of the South African Astronomical Observatory. Except for the two brightest stars, HD 50896 and HD 86161 which were observed with the Strömgren-b filter, observations were made through the Johnson-B filter. These choices were made out of purely practical considerations. Wolf–Rayet stars usually have strong emission features in these bands which

Table 1. A list of the programme and comparison stars. Stars within a group were taken together in correcting for transparency variations.

WR	HD	Sp	Remarks
WR 6	HD 50896	WN 5	P = 3.7658 d, quasi–periodic variations.
	HD 49028	B8 IV	1988
	HD 52092	B3V	1988
	HD 55857	B0.5V	1986, 1987, 1988
	HD 56342	B3V	1986, 1987
WR 16	HD 86161	WN 8	Quasi–periodic variations with P ≃ 17.5 d.
	HD 88907	B2V	
	HD 89104	B2IV–V	
WR 17	HD 88500	WC5	Constant.
WR 21	HD 90657	WN4+O4–6	Eclipsing.
WR 22	HD 92740	WN7+abs	Eclipsing.
WR 23	HD 92809	WC6	Constant.
WR 24	HD 93131	WN7+abs	Var. ΔB = 0.02 mag.
WR 25	HD 93162	WN7+abs	Constant.
WR 40	HD 96548	WN8	Var., P = 2.5 d, 7.25 d., quasi periodic.
WR 42	HD 97152	WC7+O7V	Eclipsing.
	HD 89203	B7III	
	HD 93484	B3V	
	HD 94097	B3V	Var., ΔB = 0.02 mag.
	HD 96947	B4V	Var., ΔB = 0.04mag., P = 3.472 d.
	HD 98314	B9III	
WR 52	HD 115473	WC5	Var., ΔB = 0.01 mag.
WR 57	HD 119078	WC7	Constant.
	HD 115436	B9III	
	HD 117024	B2Ib	
	HD 119423	B3/5Vne	
WR 69	HD 136488	WC9	Var., ΔB = 0.02 mag.
WR 71	HD 143414	WN6	Var., ΔB = 0.10 mag.
	HD 137683	B9	
	HD 138276	A0	
	HD 143832	A0	
WR 78	HD 151932	WN7	Eclipsing, P = 22.7 d.
WR 79	HD 152270	WC6–7+O5	Constant.
	HD 150608	B9	
	HD 151515	O6f	
	HD 152003	B0Ia	Var., ΔB = 0.05 mag., P = 1.724 d.
WR 103	HD 164270	WC9	Eclipsing, P = 1.75 d.
	HD 163274	B9	
	HD 164455	B5	

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changes the effective wavelength of the filter. The resulting difference in extinction coefficient between the WR star and the comparison stars leads to an apparent 12-hr periodicity, as this is the time interval between successive extinction maxima. This was not a serious problem: the amplitude is very low and the cause is immediately obvious.

We generally chose nearby B-type stars as comparison stars to correct for transparency variations. As many of the WR stars are within a few degrees of one another, it was possible to use the same comparison stars for more than one programme star. A list of the programme and comparison stars is given in Table 1.

The first step in our reduction procedure was to obtain extinction coefficients for each night by means of the comparison stars. These were observed over a large air mass range. The results were found to be close to the mean yearly extinction values for Sutherland. After correcting for extinction, we divided the stars into several groups. Within each group the stars were sufficiently close that differential extinction effects were negligible. Transparency corrections for each group were calculated using the comparison stars. The data are published elsewhere (Balona, Egan & Marang 1989).

Variable comparison stars were detected and eliminated by examining the mean nightly residuals for each comparison star relative to the average of the whole group. As an additional check we examined the periodogram for each comparison star. This allowed detection of low-amplitude periodic variability. The mean standard deviation for the comparison stars was 3.3 millimag per observation. The typical noise level in the periodogram was less than 2 millimag. Thus we are confident of detecting coherent periodic variations with amplitudes not less than 5 or 6 millimag, which we consider to be our lower limit of detection.

We employed two methods of searching for periodicities. One is the standard Fourier periodogram analysis technique for unequally spaced data; the other is a modification of Steelingwerf's (1978) phase-dispersion minimization (PDM) technique. The first method is suited to the case where the underlying variation is approximately sinusoidal, but it can give misleading results when the variations are highly non-sinusoidal. The PDM technique is more general, but one has to be careful of spurious periodicities. In each case the final decision rests on a careful examination of the light curves given by the two methods.

3 Results

3.1 HD 50896

Firmani *et al.* (1980) discovered this WN5 star to be variable in light and radial velocity with a period of 3.763 d. This was subsequently confirmed by Cherepashchuk (1981) and Lamontagne, Moffat & Lamarre (1986). As mentioned in the introduction, the variations have been interpreted in terms of the orbital effect of a compact companion.

We observed this star for three consecutive seasons. Fig. 1 is a montage of all published photometry (data sets containing only a few observations were not included, however). It shows the large variability of the light curve. Our data show that the familiar sharp maximum was present during 1987 but not in 1986 or 1988. During the observing run in 1987 we witnessed a sharp drop in the amplitude of this feature by a factor of two during a 2-week interval.

A period analysis using all available data, but only those light curves which show the sharp maximum, indicates a period $P = 3.7658 \pm 0.0007$ d. However, it is not possible to select a period in which the phases of the sharp maxima for 1975 and 1976 remain at phase zero. It appears that a rather sudden period change occurred sometime between 1976 and 1977 assuming that the feature seen in 1975 and 1976 is the same as the one seen at other times.

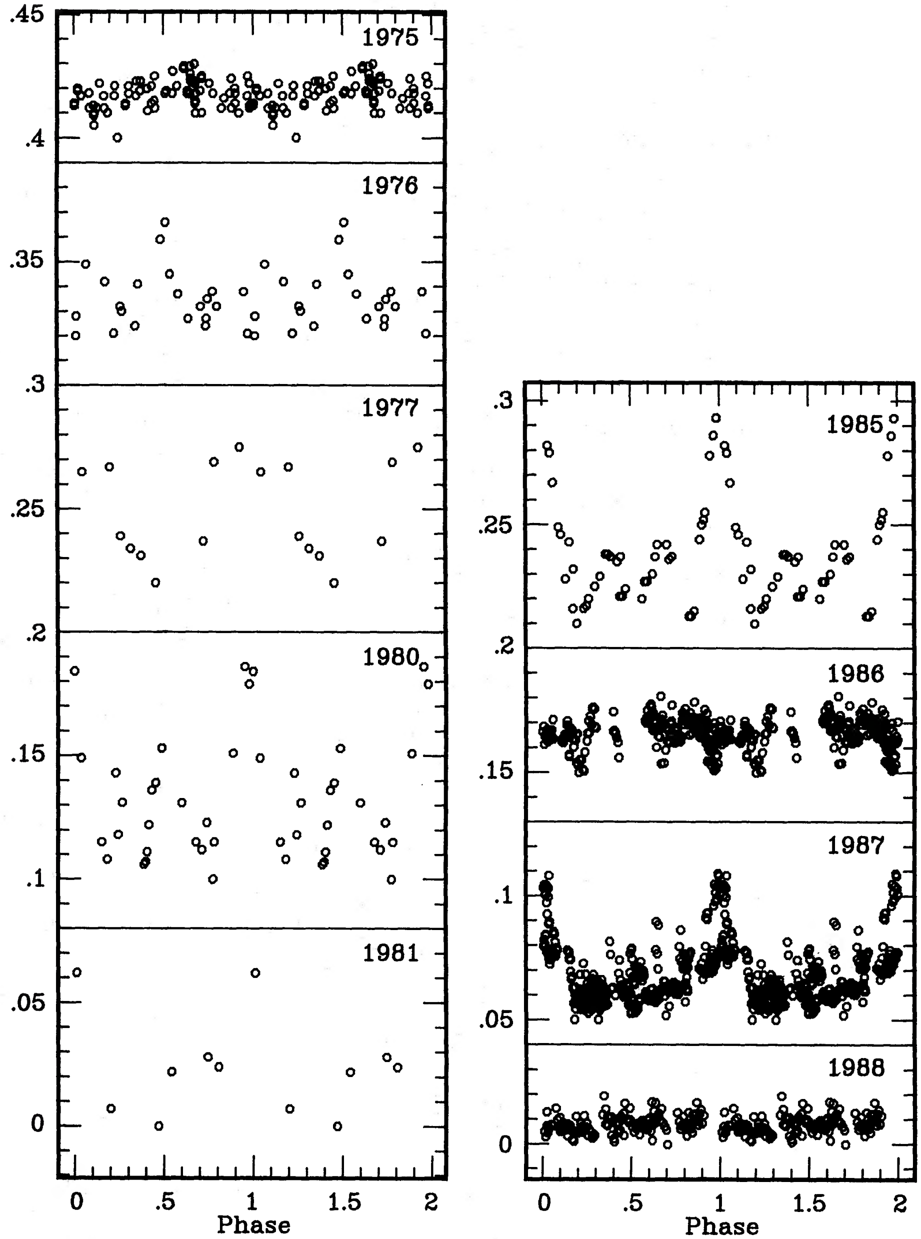

Figure 1. A montage of all available photometry for HD 50896. The period is 3.7658 d, the epoch of phase zero is JD 2440000.300.

Subsidiary peaks are often seen in the light curve; those in 1980 and 1985 being particularly prominent. One could conjecture that the peak seen in 1975 and 1976 is one of these subsidiary peaks and that the main feature is absent at this time. This avoids the necessity of a period change, but in any case it is difficult to reconcile the light curve with a simple compact binary model.

We examined our data in more detail for low-amplitude features akin to the subsidiary peaks seen in the past. Gosset & Vreux (1987) analysed the published photometry and suggest the presence of a second period at or close to one-third of the basic period, P. If it is exactly one-third of P, then it is merely an harmonic and simply indicates a non-sinusoidal variation. If it is significantly different from this value, then the possibility arises of true multiperiodicity which

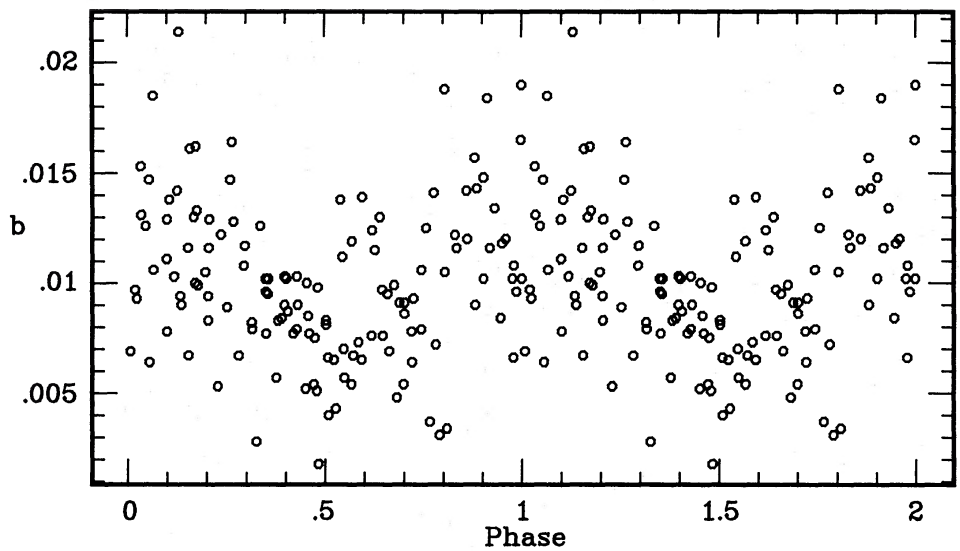

Figure 2. The light curve of HD 50896 for the 1988 season showing a period of 1.18 d. This is distinctly different from one-third of the basic period.

could, as they suggest, be a result of non-radial pulsation. The data they analysed are insufficient to resolve this question.

Our data show that another periodicity is indeed present during 1988, though not in 1986 or 1987. A periodogram shows significant power at a period of 1.18 d, giving the light curve shown in Fig. 2. The important point is that this period is *significantly different* from $P/3$; indeed a plot with the data phased with P shows no sign of periodic variations (Fig. 1). Since this variation is not observed during every season, it is probably a transient phenomenon similar to the subsidiary features seen at other times. It is not a sub-multiple of the orbital period, so it does not seem possible to account for this phenomenon in terms of the supposed compact companion. As will become evident, transient, quasi-periodic feature seem to be present in many WR stars.

3.2 HD 86161

Moffat & Niemela (1982) found this star to have a photometric period of 5.365 d; they argue for a period twice as long on the basis of spectroscopic data. They regard it as another example of a compact object in orbit around a WR star. The period was confirmed by Lamontagne & Moffat (1987), who used the same comparison star HD 86199. Drissen, St-Louis, Moffat & Bastien (1987) failed to detect any periodic variations in polarization.

Manfroid *et al.* (1987) have recently shown that HD 86199 is in fact a variable with a period of 5.494 d. Thus the period attributed to the WR star by the previous workers is incorrect. Their own rather limited data suggest the presence of two periods: 1.3 and 2.5 d. On this basis they suggested non-radial pulsation as the most likely cause of variability.

Our observations shown in Fig. 3 indicate that HD 86161 is indeed variable; periodogram analysis gives a most likely period of 17.54 d. The corresponding light curve is shown in Fig. 4. There is no evidence for multiperiodicity; removing a best-fitting Fourier curve with this period leads to a noise spectrum with a rms scatter of 16 millimag, which is much larger than the observational error.

An examination of Fig. 3 shows a lengthening of the period between maxima. This indicates that the variation is not strictly periodic, though there are not enough cycles to prove

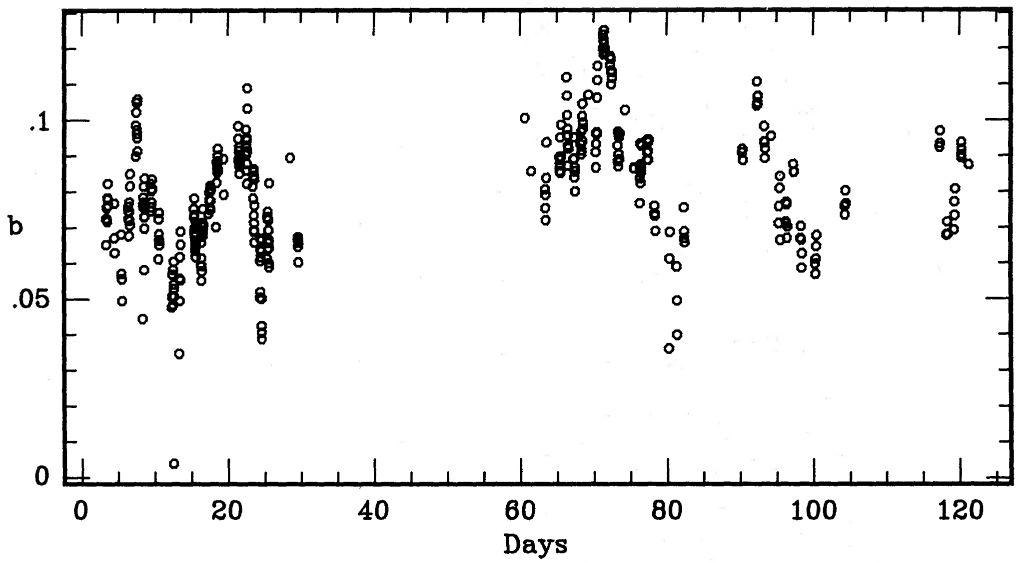

Figure 3. Strömgren-*b* photometry of HD 86161 showing quasi-sinusoidal variations.

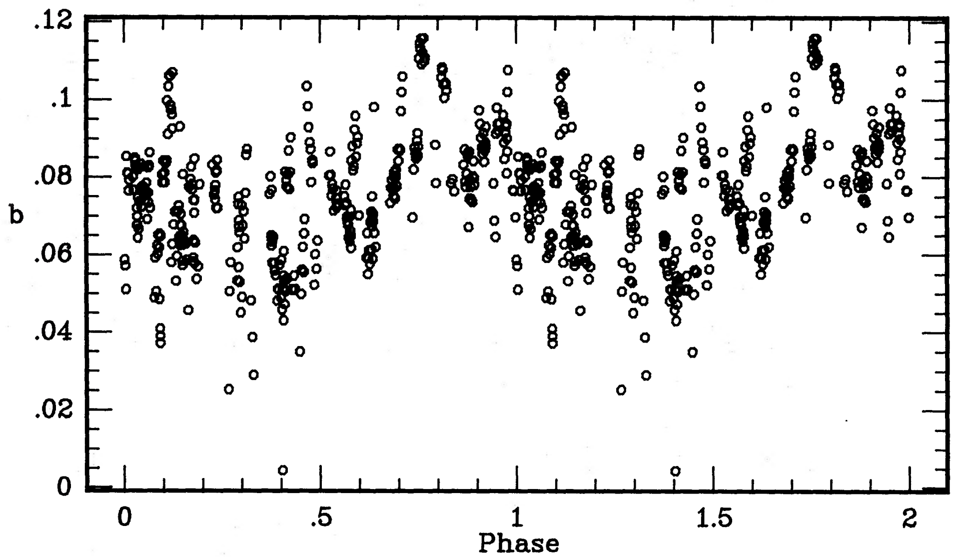

Figure 4. The light curve of HD 86161 phased with the best period of 17.54 d.

otherwise. It is likely that this is another example of the quasi-periodic variations seen in HD 50896. The semi-amplitude of the radial-velocity curve ($K=6$ km s^{-1}) is the lowest ever reported for a Wolf–Rayet star. This suggests that it is not a binary and that the 17.54 d quasi-period is not connected with the presence of a companion.

3.3 HD 90657

Niemela & Moffat (1982) show that this star is a double-lined spectroscopic binary with an O-type companion in a nearly circular orbit of 8.255 d. They also obtained photometric observations which show a single broad minimum when phased with the spectroscopic period.

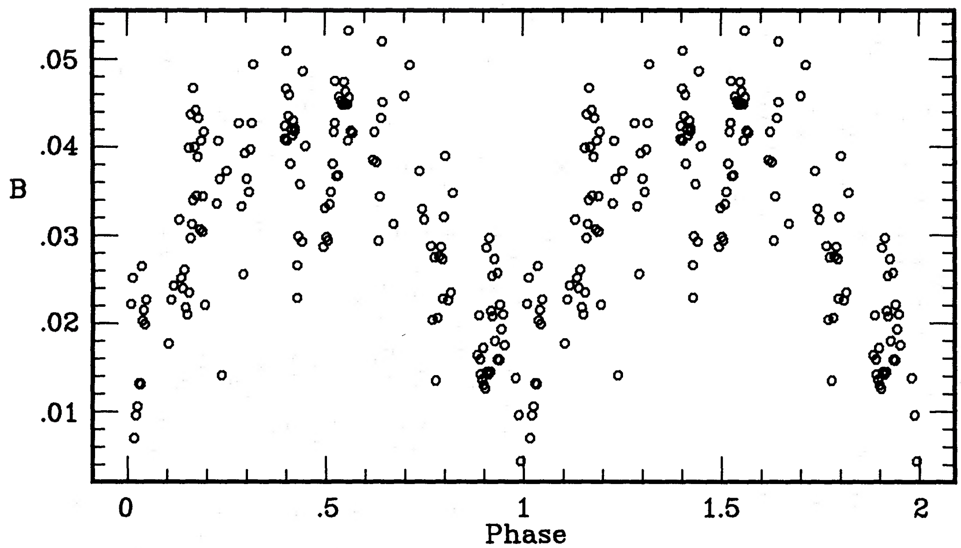

Figure 5. The light curve of HD 90657 phased with the spectroscopic elements ($P=8.255$ d); phase zero occurs when the WR star is in front. There is a suggestion of a secondary minimum at phase 0.5.

The best period obtained from our data is 8.197 d, which is not significantly different. The resulting light curve is shown in Fig. 5.

Minimum light is at phase zero which occurs when the Wolf–Rayet star is in front of the O4–6 companion. There is some indication of a narrow secondary minimum, which corresponds to the partial occultation of the Wolf–Rayet atmosphere by the O star. If this is real, it presents a problem as a narrow secondary minimum implies a narrow primary minimum, which is not observed. We were not able to refine the period as there is too large a time interval between the observations.

3.4 HD 92740

This is a single-line spectroscopic binary in an eccentric orbit ($e=0.6$) with a period of 80.35 d (Moffat & Seggewiss 1978; Conti, Niemela & Walborn 1979). The published light curves show small, non-periodic changes of a few hundredths of a magnitude.

We observed a single eclipse of short duration with a depth of nearly 0.1 mag as shown in Fig. 6. Unfortunately, poor weather prevented observations at the predicted time of the next eclipse. The figure shows a plot of the phase diagram using the ephemeris from the spectroscopic orbit. Adopting the ephemeris of Moffat & Seggewiss (1978), we find that at mid-eclipse the Wolf–Rayet component is in front. If the eclipse is total, it means that the secondary is about 2.5 mag fainter than the WR star. This is consistent with the companion being an O-type star. The existence of an eclipse in such a wide system is exceptional; owing to incomplete phase coverage, it is not possible to confirm the presence of a secondary eclipse.

Conti *et al.* (1979) suspect the presence of faint absorption lines near the limit of detectability in their spectra. They suggest that these lines are due to the secondary since they are significantly redward or violet-displaced from several Balmer or He II lines.

A significant amount of variability appears to be present *outside* eclipse. The quasi-periodic character of these variations are remarkably similar to what is seen in HD 50896 and HD 86161. These small-scale modulations are also visible in the polarization data of Drissen *et al.* (1987). We regard this is a further example of quasi-periodic variability in WR stars.

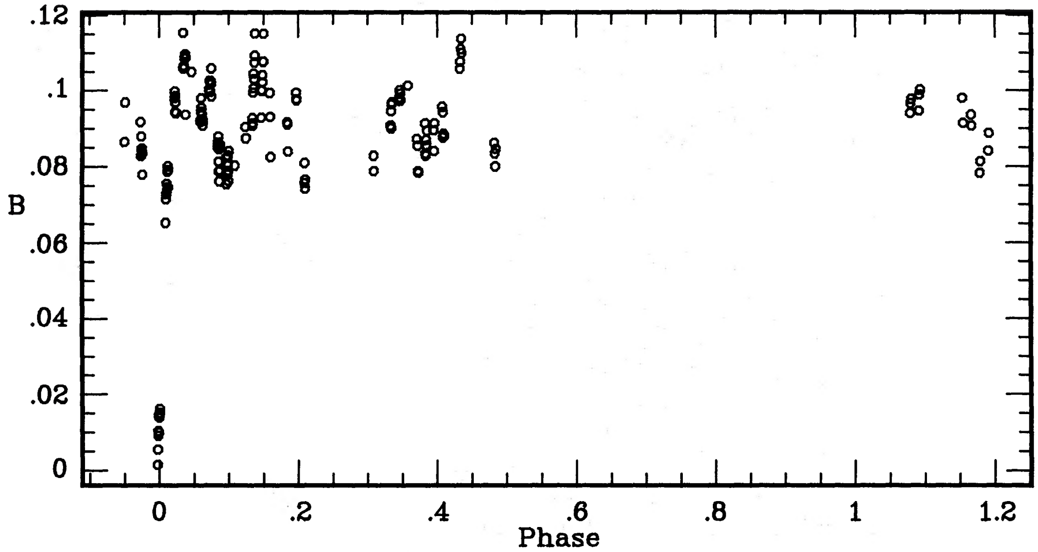

Figure 6. Johnson-*B* observations of HD 92740 plotted with time. The phase refers to the spectroscopic elements ($P = 80.35$ d). An eclipse occurs at phase zero when the WR component is in front. Bad weather prevented observation of a second eclipse. Notice the quasi-periodic variations outside eclipse.

3.5 HD 96548

This is a well-known large amplitude variable (Moffat & Isserstedt 1980). These authors obtained a double-wave light curve with a period of 4.762 d and 0.04 mag amplitude. They suggest the presence of a compact companion from an analysis of the radial velocity curve. Later, Moffat (1983) revised the period to 4.1584 d using additional radial velocities. Smith, Lloyd & Walker (1985) deduced a period of 5.879 d or its one-day alias. Lamontagne & Moffat (1987) obtained a period of 4.7 d. Most recently, Gosset *et al.* (1989) re-analysed the published data together with new photometric data and deduced a period of 6.25 d. Drissen *et al.* (1987) discovered large variations of polarization in the star with time scales of less than one day, but no definite periodicity could be found.

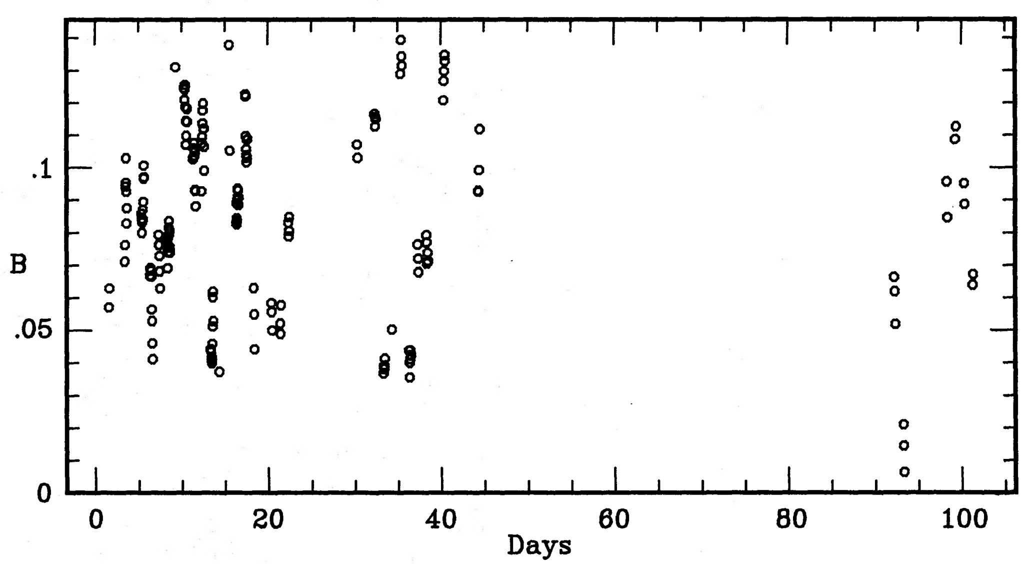

Figure 7. Johnson-*B* observations of HD 96548 showing large-amplitude variations.

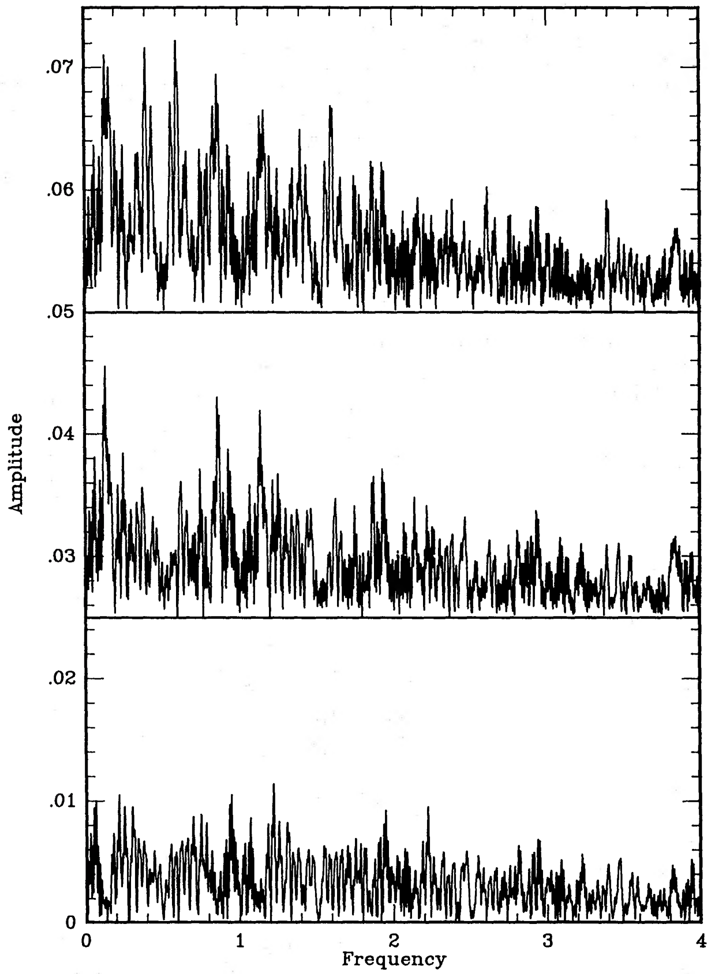

Figure 8. Periodograms of HD 96548: top panel = raw data; middle panel = periodogram of the residuals of a single-period Fourier fit (P_1 = 1.67 d); bottom panel = periodogram of the residuals of a two-frequency Fourier fit (P = 1.67 d, P = 7.25 d).

Fig. 7 shows the run of magnitude with time for our observations. Fig. 8 shows the corresponding Fourier periodogram in the top panel. The highest peak occurs at a frequency of 0.600 d^{-1} or its one cycle d^{-1} alias at 0.400 d^{-1}. The latter frequency is the same as that found in data set I of Gosset *et al.* (1989) and has a very large probability of being real. The middle panel is the periodogram when a signal with this frequency is removed from the data. There is a second periodicity with a frequency of 0.138 d^{-1} and its aliases. This is significantly different from 0.160 d^{-1} which appears to be present in most data sets. When the best-fitting Fourier curve with frequencies of 0.400 (or 0.600) and 0.138 d^{-1} is removed from the data, no further periodicities can be detected (bottom panel). However, the rms scatter is considerably larger than the expected observational error.

From our data, it would seem that there is considerable evidence for supposing this star to be multiperiodic with P_1 = 2.5 d (or 1.67 d) and P_2 = 7.25 d. However, it is clear that these frequencies are not stable from season to season as is evident from the conflicting results obtained by different authors. Although the periods do not seem to be repeatable, there is a definite trend for a periodicity of about one week to be present in all data sets, a fact already noted by Gosset *et al.* (1989). A secondary frequency of about 0.4 d^{-1} (or its alias of 0.6 d^{-1}) is also recovered from most data sets.

The evidence of recurring quasi-periodicities is very strong for this star. It is certain that a simple orbital model will not work, especially as there is more than one quasi-period present.

3.6 HD 97152

This is a double-line spectroscopic binary (WC7+O7V) in a nearly circular orbit with a period of 7.886 d (Davis, Moffat & Niemela 1981). They found the star to be constant in light to within 0.01 mag, but we find that the light does vary with the spectroscopic period (Fig. 9). Phase zero occurs when the Wolf–Rayet star is in front of the O companion, though we find minimum light to occur at phase 0.3. This difference probably implies that the ephemeris needs some correction. A smooth curve fits the data to 4 millimag. The light curve is most likely due to phase-dependent attenuation of light from the O star in the WR wind. Polarization data by St-Louis *et al.* (1987) indicates an orbital inclination $i = 43.5°$.

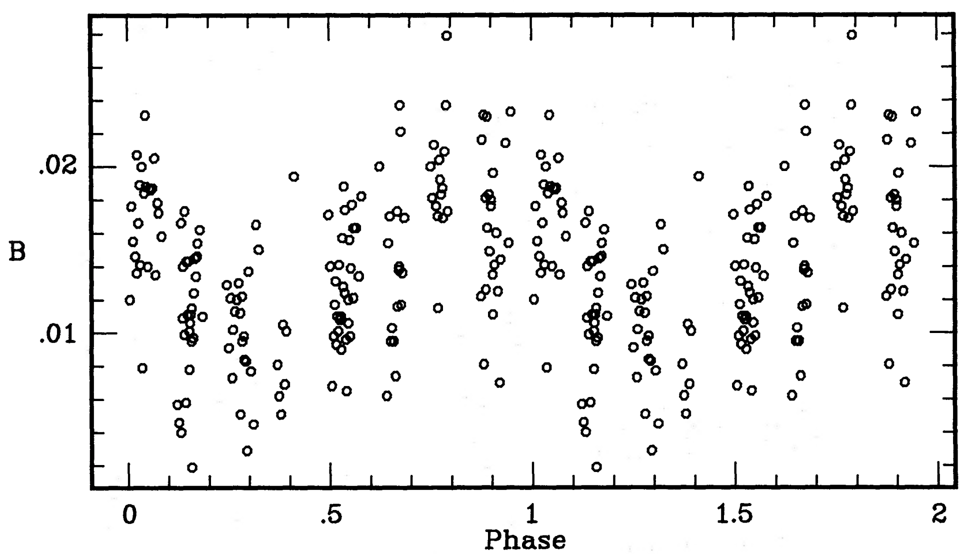

Figure 9. Light curve of HD 97152 using the spectroscopic ephemeris ($P = 7.886$ d). Phase zero occurs when the WR star is in front of the O star.

3.7 HD 143414

HD 143414 was studied by Isserstedt, Moffat & Niemela (1983) who obtained some photometry and extensive spectroscopy. They derived a spectroscopic orbit with a period of 7.690 d. From its high peculiar radial velocity they suggest that it is a runaway star. Their limited photometry showed a sinusoidal light curve with an amplitude of about 0.07 mag. Our data shows a significant increase in brightness of nearly 0.1 mag during a three-month interval. Even allowing for this trend, we are unable to confirm the spectroscopic period. The strongest peak occurs at a frequency of 0.57 d^{-1} corresponding to a period of 1.75 d, but the scatter is rather large.

3.8 HD 151932

Seggewiss & Moffat (1979) conclude that this star does not have a binary companion; their photometry indicates that the star is constant. On the other hand, Magain, Vreux & Manfroid (1987) found considerable photometric activity during 1986.

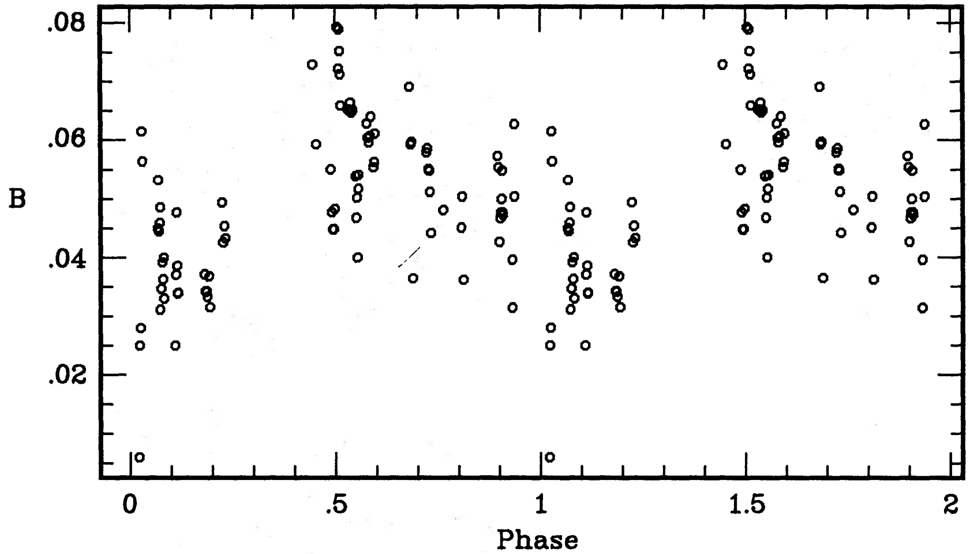

Figure 10. Light curve of HD 151932 showing the 22.7 d periodicity.

Our data indicate that the star is certainly variable. The periodogram gives a significant peak at a period of 22.7 d giving the light curve shown in Fig. 10. While this result needs confirmation, it suggests that WR 78 is either a binary or else this is one more example of quasi-period photometric activity.

3.9 HD 152270

This star is a member of the open cluster NGC 6231 which is the nucleus of the Sco OB 1 association. Absorption lines from the O5 companion are visible. Seggewiss (1974) deduced a spectroscopic orbit with a period of 8.893 d. The WR star is surrounded by a shell expanding at 1688 km s^{-1} which takes part in the star's binary motion. We find little, if any photometric variability. The light curve phased with the spectroscopic period shows no evidence of periodicity; we conclude that the inclination is probably too low to produce eclipses. Indeed, St-Louis *et al.* (1987) find $i = 44.8°$ from polarimetric observations. They obtained a light curve showing a sinusoidal variation of amplitude 0.025 mag when phased with the spectroscopic period. This is probably caused by attenuation of the light from the O-star by the WR wind. The fact that periodic light variations are not always seen implies a marked change in wind density with time.

3.10 HD 164270

Moffat, Lamontagne & Cerruti (1986) have postulated that WR 103 is a binary with 1.75 d period. In order to explain a deep eclipse-like variation many years ago, they also assume the presence of a precessing disc. Our data tend to support this period (Fig. 11), though this requires confirmation since we obtained only 42 observations.

4 Conclusions

Our main conclusion is that there is no evidence whatsoever for periods of the order of an hour or two which would arise from p-mode pulsations in Wolf–Rayet stars. We have discovered

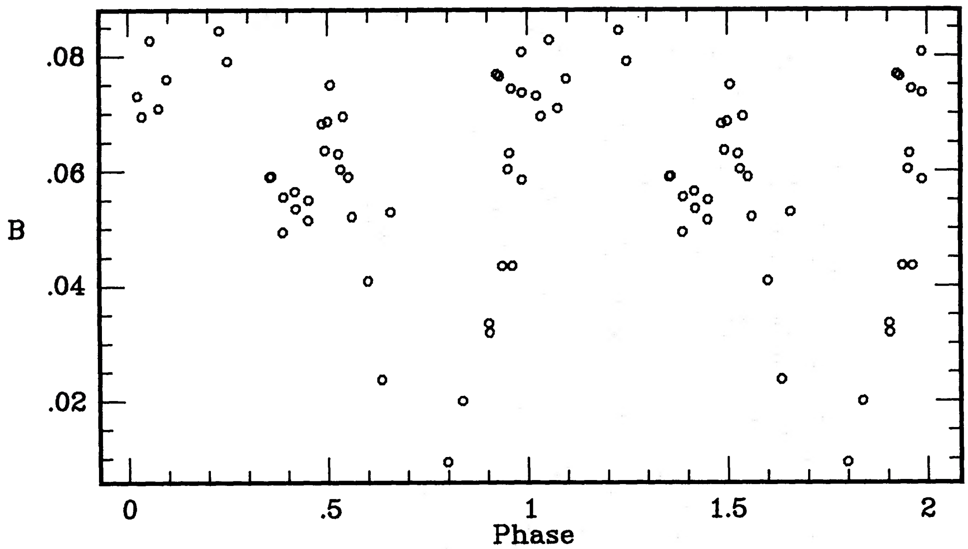

Figure 11. Light curve of HD 164270 showing the 1.75 d periodicity.

several examples of a quasi-periodicity. While it is always possible to invoke non-radial g-mode oscillations with changing periods, this model is too *ad hoc* to be taken seriously. The most probable explanation for this phenomenon is likely to be found in the material of the stellar wind. We suggest that density enhancements in the wind moving outwards from the star are perhaps responsible. This model predicts the gradually increasing period which is seen in HD 86161. However, it does not seem possible to easily explain the dual periods of HD 96548 unless one supposes that the short period (2.5 d) is the rotation period of the star. This is reasonable as this periodicity seems to stay constant, while it is the longer period of about one week which changes.

We did not find any star whose light curve resembles HD 50896 for which a compact companion is suspected. Either the number of WR stars with compact companions is small or their manifestation in the light curve is strongly dependent on orientation. We also find that a single, constant period is not sufficient to explain the observations as this leads to a shift of 0.5 periods for the 1976 and 1977 observations. We suspect that even in this star, where the period is indeed very constant, that the light curve may reasonably be explained in terms of a circumstellar density enhancement. We then have to suppose that the material is coupled to the rotation of the star via a magnetic field in order to achieve a constant period. This model has the advantage of being able to accommodate the 0.5 period shift if the assumption of a dipole field is made. Whether this assumption can be justified remains to be seen, but it is very clear that the simple model of an orbiting compact companion is not sufficient to explain all the observations.

The scatter in the light curves is always considerably larger than expected from observational error. This implies the existence of random brightness fluctuations possibly associated with the stellar wind. Moffat *et al.* (1988) have discovered small, narrow emission bumps moving across an emission profile. These are thought to be due to outward moving condensations in the stellar wind and could give rise to the observed random brightness fluctuations.

Acknowledgment

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