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# A high precision photometric investigation of the micro-variations of Wolf-Rayet stars<sup>★</sup>

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**Summary.** Walraven *VBLUW* photometric monitoring of 7 Wolf-Rayet stars made in March/April 1986 is presented and discussed. The sample consists of 4 real or suspected single line spectroscopic binaries (SB1) and 2 single stars, all of spectral type WN, and 1 star of spectral type WC. The light and colour variations, caused by binary modulation and/or by an intrinsic random mechanism are shown and discussed. Correlation diagrams of colours versus brightness reveal that the fluxes in the *L* and *U* bands, where normal stars have a Balmer limit, at least if hydrogen is abundant enough, often vary 10–20% more strongly than those in the other band passes. Yet *L* and *U* have the smallest emission line content. This, together with the fact that for different stars the systematic correlations between brightness- and colour variations often look similar, supports the view that continuum variations by temperature effects are the cause.

The possibility is briefly discussed that the pseudo-photosphere (the main layer in the envelope from which we receive most of the continuum light) is not uniformly illuminated because of dynamical inhomogeneities, resulting in the formation of temporarily hotter eddies or blobs.

In 1974–1976 the star WR 6 = EZ CMa = HD 50896 showed a strong far-ultraviolet deficiency (van der Hucht et al. 1979), while our *W* band ( $\lambda_{\text{eff}} = 3236 \text{ \AA}$ ) showed a strong excess due to the presence of two very strong He emission lines. The long-term variability of the light curve shape, the visual brightness and the He emission line strengths are discussed in terms of an increase of the transparency in the outer parts of the envelope.

It is demonstrated that photometric reddenings of WR stars on the basis of this photometric system are sensitive to spectral line contamination and thus cannot be trusted.

**Key words:** photometry – variable stars – Wolf-Rayet stars

## 1. Introduction

Evidence has been accumulating during the last decade that most of the Wolf-Rayet stars exhibit small scale size photometric variations with different characteristics up to  $\sim 0^{\text{m}}.1$  (cf. Moffat and Shara, 1986; Lamontagne and Moffat, 1987). Also, variations in radial velocity, in spectral lines and in linear polarization have

been reported. A certain percentage of these variations could be due to a rotating, distorted WR star, because of the proximity of a compact companion, while the single stars sometimes show micro-variations of a presumably random nature. Often such random intrinsic variations are superimposed on the light curve of a binary system, giving it a very noisy appearance and making it difficult to find the period of revolution. However, there are for two cases some indications that light variations also may be caused by a double periodicity, viz. WR 6: Gosset and Vreux (1987) and WR 40: Smith et al. (1985). For reviews and references we refer to van der Hucht et al. (1981), Cherepashchuk and Aslanov (1984), Jeffers et al. (1985), Moffat and Shara (1986) and Vreux (1985, 1987).

So far only a few photometric studies of WR stars have revealed colour variations in addition to magnitude variations cf. Moffat and Isserstedt (1980), Moffat and Niemela (1982), Smith et al. (1985) and van Genderen and van der Hucht (1986, hereafter called Paper I). Since the colour variations are much smaller than the magnitude variations, often  $\sim 0^{\text{m}}.02$  or smaller, they cannot be detected easily. In order to obtain some insight into the general characteristics of the colour variations, especially those of the random fluctuations, high precision photometry of a larger number of WR stars is necessary. Therefore we started a systematic, high precision photometric program (Walraven *VBLUW* system) of seven WR stars of which, according to the literature, three are single and four have a companion (see Table 3).

## 2. The observations and reductions

The observations were made with the 90-cm Dutch telescope at ESO, La Silla, Chile, equipped with the *VBLUW* photometric system of Walraven, during the interval from March 25/26 to April 5/6, 1986. A few additional observations were obtained for one star by P. Houtekamer in May 1986 and by H.J.A. Röttgering in June/July 1986, at our request. A detailed description of the photometric system is given by Lub and Pel (1977) and references therein. The diaphragm aperture was  $16''$ . In order to obtain nightly averages relative to the comparison star with standard deviations (s.d. or  $\sigma$ ) as small as  $\lesssim \pm 0^{\text{m}}.002$ , each program star was measured 6–8 times, alternated by the observation of a nearby comparison star. Such a series of observations lasts about 20 min.

In all figures (1–8) an error bar is drawn, indicating the *upper limit* of the *mean error* ( $\sigma/\sqrt{n}$ ) of each data point, viz.  $\pm 0.0005 \log$

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★ Observations collected at the ESO, La Silla, Chile

**Table 1.** Photometric data of the comparison stars (listed in order of decreasing brightness) calibrated in the *VBLUW* and the *UBV* system (with subscript J) and their standard deviations (see Sect. 2)

HD	Spectral type	<i>V</i>	<i>V</i> – <i>B</i>	<i>B</i> – <i>U</i>	<i>U</i> – <i>W</i>	<i>B</i> – <i>L</i>	<i>V<sub>J</sub></i> (mag)	<i>(B</i> – <i>V<sub>J</sub>)<sub>J</sub></i> (mag)	Program star(s)
		(log intensity)							
156293 <sup>f</sup>	B9V <sup>a</sup>	0.4497 ±0.0019	–0.0175 ±0.0015	0.3621 ±0.0010	0.0807 ±0.0013	0.1160 ±0.0033	5.762 ±0.005	–0.055 ±0.004	WR 90
50853 <sup>d</sup>	A1 <sup>b</sup>	0.2588 ±0.0014	0.0053 ±0.0013	0.4350 ±0.0010	0.1086 ±0.0009	0.1616 ±0.0018	6.238 ±0.004	0.004 ±0.003	WR 6
96568 <sup>c</sup>	A3V <sup>c</sup>	0.1921 ±0.0017	0.0482 ±0.0010	0.4785 ±0.0012	0.1439 ±0.0013	0.1976 ±0.0021	6.401 ±0.004	0.112 ±0.003	WR 40
86000	B8/9(IV) <sup>c</sup>	–0.4996 ±0.0017	–0.0047 ±0.0012	0.2518 ±0.0010	0.0529 ±0.0011	0.0985 ±0.0013	8.134 ±0.004	–0.022 ±0.004	WR 16
93712	A0V <sup>c</sup>	–0.8293 ±0.0014	0.0072 ±0.0010	0.4031 ±0.0013	0.0867 ±0.0016	0.1600 ±0.0018	8.958 ±0.004	0.008 ±0.003	WR 22, 24, 25

<sup>a</sup> Houk (1978)<sup>b</sup> Hoffleit (1982)<sup>c</sup> Houk and Cowley (1975)<sup>d</sup> The same comparison star used by Lamontagne et al. (1986)<sup>e</sup> The same comparison star used by Moffat and Isserstedt (1980)<sup>f</sup> Slightly variable especially in the ultra violet band-passes *L* and *U*

intensity scale (it is customary in the *VBLUW* system to apply a log-intensity scale instead of magnitudes). Thus the total length of the error bars amounts to 0.0010 or 0<sup>m</sup>0025.

The constancy of the comparison stars was checked by a comparison with each other of their nightly averages on the natural *VBLUW* system, calibrated by means of standard stars regularly measured throughout each night.

Table 1 lists (in order of decreasing visual brightness) these calibrated average photometric parameters of the five comparison stars used and their s.d.'s based on the eleven nightly averages. It must be emphasized that these s.d.'s are not comparable with those of the nightly averages variable minus comparison star. The latter are always much smaller. The reason is that the distances in the sky between the comparison stars and the standard stars are much larger than between the comparison stars and the program stars. The *V* of the *UBV* system (with subscript J and on a magnitude scale) was obtained with the formula:

$$V_J = 6.885 - 2.5[V + 0.030(V - B)]$$

Corresponding values of  $(B - V)_J$  were obtained from  $V - B$  with the aid of the formula:

$$(B - V)_J = 2.571(V - B) - 1.020(V - B)^2 + 0.500(V - B)^3 - 0.010$$

Both formulae are from Pel (1985).

The s.d.'s given in Table 1 are satisfactorily small, so that the comparison stars can be considered as constant stars during the observing period, with the exception of the brightest comparison star HD 156293 (B9 V). This star is not completely stable. The most variable part of its continuum is apparently that in the *L* band ( $\lambda_{\text{eff}} = 3837 \text{ \AA}$ ), which contains the Balmer limit. (Fig. 8, Sect. 3.5, shows the constant WR star WR90, relative to HD 156293. The wavy pattern in *B* – *L* with a time scale of  $\sim 6^d$  and an amplitude of  $\sim 0^m01$  must be due to HD 156293 and not to WR 90. Also *B* – *U* shows this tendency, but more

weakly. The *U* band ( $\lambda_{\text{eff}} = 3623 \text{ \AA}$ ) lies mainly at the short wavelength side of the Balmer jump).

For still unknown instrumental reasons, the s.d.'s in the averages of eleven nights of the colour index *B* – *L* are always systematically larger than the other photometric colour indices. This has no effect whatsoever on the *B* – *L* colours of the program stars relative to the comparison stars.

Table 2a lists the individual observations for the three WR stars WR 6, WR 16 and WR 40, which clearly vary in brightness, and one or more colour indices relative to their respective comparison stars. Table 2b lists the individual observations in visual light only (the colours are practically constant) of WR 22, WR 24, and WR 25. Table 2c lists the visual observations of the constant star WR 90, thus illustrating the small scatter attainable.

Table 3 gives the average photometric parameters of all program stars, including the constant star WR 90, and the s.d.'s. It must be emphasized that these s.d.'s also include the instrumental and atmospheric scatter, as for the s.d.'s of the comparison stars in Table 1. The s.d.'s of Table 1 (comp. stars) and Table 3 (progr. stars) are thus all based on eleven nightly averages calibrated with standard stars. It is obvious that most of the s.d.'s of the program stars in the *V* band (Table 3) are significantly larger than those for the comparison stars (Table 1), proving that most of them are variable. Since the colour variations of the program stars are much smaller or for some cases even absent, the s.d.'s listed in Table 3 are only for a few cases significant larger than those for the comparison stars listed in Table 1. Clear evidence of the variability of some of the colours can best be obtained by the detected correlations in the diagrams colour versus brightness (Sect. 3).

If one derives means and s.d.'s of the nightly averages listed in Table 2, one obtains values different from those in Table 3. The reason is that the data in Table 2 are relative with respect to the comparison stars, while in Table 3, the values were obtained by a comparison with standard stars.

**Table 2a.** The individual relative  $VBLUW$  data of the program stars and the magnitude  $V$  of the  $UBV$  system (with subscript J)

J.D.-2440000	$\Delta V$	$\Delta(V - B)$	$\Delta(B - U)$ (log intensity)	$\Delta(U - W)$	$\Delta(B - L)$	$V_J$ (mag)
<u>WR 6 – HD 50853</u>						
6516.542	-0.2349	-0.0210	-0.4979	-0.2392	-0.1712	6.826
6517.597	-0.2521	-0.0205	-0.4960	-0.2435	-0.1683	6.869
6518.590	-0.2448	-0.0205	-0.4956	-0.2429	-0.1691	6.851
6519.510	-0.2542	-0.0206	-0.4951	-0.2437	-0.1693	6.875
6521.604	-0.2509	-0.0202	-0.4949	-0.2422	-0.1686	6.866
6522.549	-0.2528	-0.0204	-0.4967	-0.2425	-0.1695	6.871
6523.549	-0.2508	-0.0206	-0.4970	-0.2429	-0.1708	6.866
6524.542	-0.2504	-0.0207	-0.4970	-0.2416	-0.1693	6.865
6525.583	-0.2437	-0.0200	-0.4961	-0.2400	-0.1699	6.848
6526.597	-0.2460	-0.0207	-0.4953	-0.2382	-0.1686	6.854
<u>WR 16 – HD 86000</u>						
6516.569	-0.0591	0.1632	-0.2009	-0.0014	-0.0567	8.270
6517.622	-0.0709	0.1618	-0.2005	-0.0023	-0.0564	8.299
6518.684	-0.0724	0.1625	-0.1988	-0.0039	-0.0546	8.303
6519.642	-0.0736	0.1628	-0.1999	-0.0028	-0.0558	8.306
6521.632	-0.0629	0.1622	-0.2001	-0.0028	-0.0558	8.279
6522.594	-0.0787	0.1626	-0.1993	-0.0026	-0.0559	8.319
6523.580	-0.0594	0.1632	-0.2026	-0.0012	-0.0578	8.271
6524.573	-0.0658	0.1616	-0.2010	-0.0024	-0.0563	8.287
6525.625	-0.0663	0.1643	-0.1999	-0.0010	-0.0559	8.288
6526.635	-0.0699	0.1630	-0.1999	-0.0027	-0.0563	8.297
<u>WR 40 – HD 96568</u>						
6515.837	-0.5248	0.0383	-0.4571	-0.1253	-0.1816	7.710
6516.670	-0.5080	0.0381	-0.4586	-0.1259	-0.1812	7.668
6517.757	-0.5323	0.0378	-0.4558	-0.1281	-0.1829	7.729
6518.778	-0.4967	0.0392	-0.4585	-0.1251	-0.1820	7.640
6519.743	-0.5032	0.0382	-0.4608	-0.1250	-0.1845	7.656
6521.757	-0.5164	0.0377	-0.4591	-0.1273	-0.1842	7.689
6522.712	-0.5246	0.0360	-0.4564	-0.1308	-0.1831	7.710
6523.704	-0.5180	0.0370	-0.4597	-0.1263	-0.1849	7.693
6524.639	-0.5371	0.0358	-0.4540	-0.1306	-0.1815	7.741
6525.750	-0.5270	0.0387	-0.4562	-0.1280	-0.1825	7.716
6526.667	-0.5085	0.0397	-0.4606	-0.1261	-0.1853	7.670
6556.649	-0.5110	0.0394	-0.4564	-0.1284	-0.1838	7.676
6558.559	-0.5353	0.0393	-0.4534	-0.1278	-0.1832	7.737
6609.510	-0.5364	0.0403	-0.4558	-0.1260	-0.1845	7.739
6610.507	-0.5264	0.0376	-0.4579	-0.1277	-0.1845	7.714
6612.497	-0.5126	0.0354	-0.4594	-0.1275	-0.1854	7.680
6613.519	-0.5313	0.0387	-0.4551	-0.1286	-0.1841	7.727

The quality of the calibration changes during a night due to changing atmospheric conditions, and thus the quality of the nightly averages changes also. Consequently the s.d.'s in Table 1 based on the eleven averages are usually not the same for all constant stars although they were observed in the same night. A few deviating values can seriously affect the s.d. Examples are the s.d.'s of the colour  $B - L$  of the stars WR 25 and WR 90, which are both nonvariable in this colour:  $\pm 0.018$  and  $\pm 0.0028$ , respectively. The relative large difference between the two does not mean that WR 90 is variable in  $B - L$ .

Since an observing run of 6–8 observations per night of one program star alternated by a comparison star lasted  $\sim 20$  min, the Julian Date of the middle of the series is given in Table 2 with an accuracy of  $\pm 5$  min. A complete series of observations for the three WR stars in the Carina nebula (WR 22, WR 24 and WR 25) lasted  $\sim 50$  min, since they were observed together with the same comparison star as follows: sky-c-22-24-25-c-22... etc. The eight observations of each of these WR stars were consequently distributed over  $\sim 50$  min, giving us information on their constancy within this time range. This is important in the

**Table 2b.** The individual visual brightness  $V$ , relative to HD 93712, and the visual brightness  $V_j$  in the  $UBV$  system, of the three WR stars in the Carina nebula region: WR 22, WR 24 and WR 25

J.D.-2440000	WR 22		WR 24		WR 25	
	$\Delta V$	$V_j$	$\Delta V$	$V_j$	$\Delta V$	$V_j$
6515.753	1.0210	6.401	0.9910	6.480	0.3382	8.098
6516.618	1.0282	6.383	0.9886	6.486	0.3341	8.108
6517.726	1.0205	6.403	0.9913	6.479	0.3363	8.103
6518.726	1.0212	6.401	0.9822	6.502	0.3363	8.103
6519.708	1.0234	6.395	0.9825	6.501	0.3356	8.105
6521.681	1.0214	6.400	0.9824	6.501	0.3349	8.106
6522.674	1.0251	6.391	0.9882	6.487	0.3353	8.105
6523.653	1.0217	6.400	0.9846	6.496	0.3368	8.102
6524.712	1.0196	6.405	0.9817	6.503	0.3361	8.103
6525.722	1.0276	6.385	0.9823	6.502	0.3382	8.098
6526.771	1.0257	6.390	0.9878	6.488	0.3386	8.097

**Table 2c.** The individual visual brightness  $V$  of WR 90, relative to HD 156293, and the visual brightness  $V_j$  in the  $UBV$  system

J.D.-2440000	$\Delta V$	$V_j$
6515.861	-0.4727	6.933
6516.812	-0.4728	6.932
6517.809	-0.4728	6.932
6518.840	-0.4719	6.931
6519.813	-0.4721	6.931
6521.816	-0.4731	6.934
6522.816	-0.4727	6.933
6523.806	-0.4731	6.934
6524.809	-0.4728	6.932
6525.823	-0.4719	6.931
6526.878	-0.4723	6.932

light of theoretical predictions on the existence of short time scale oscillations of the order of 15–60 min (Maeder, 1985); see Sect. 4.

### 3. The individual program stars

#### 3.1. WR 6 = EZ CMa = HD 50896

This object, of spectral type WN 5, has been investigated extensively in the visible by Firmani et al. (1980), spectroscopically in the ultraviolet by Willis et al. (1986b) and photometrically by Lamontagne et al. (1986) and Gosset and Vreux (1987). Burton et al. (1978) have detected a 3% variation in the ANS ultraviolet data. The star shows radial velocity variations (Firmani et al., 1980). The period  $P = 3^d766$  of the complex lightcurve is stable over the interval 1980–1985. The polarimetric curves are more variable in shape over months, but always modulated with this period (Moffat et al. 1986). Gosset and Vreux (1987) reanalysed the available photometric material and suspected the presence of a second period of  $1^d27$  ( $\sim P/3$ ). Variations are also known in the X-ray flux (EINSTEIN, IPC) of WR 6. Moffat et al. (1982) argued that the observed day-to-day X-ray variability (during four consecutive days) was consistent with phase-dependent

X-ray emission. White and Long (1986) report changes of its X-ray flux by a factor two within 30 minutes. The latter authors conclude that the X-ray flux of WR 6 comes either from accretion onto a white dwarf or from the accretion wake trailing away from a black hole in the wind of the WN 5 star.

Figure 1 shows the light and colour curves of our 1986 run together with the 1985 visual observations of Lamontagne et al. using their ephemeris for phase zero = maximum light:

$$\text{J.D. } 2446153.61 + 3.766E$$

Thus our observations cover nearly three cycles. It is suspected that the WR star is in front at  $\phi = 0.0$ . The relative visual brightnesses were transformed into  $V_j$  with the aid of our  $V_j$  data of the comparison star HD 50823 (Table 1), which was also used by Lamontagne et al. However, we do not exclude the possibility of a small systematic zero point difference between our  $V_j$  scale and their  $V$  scale. The latter has not been transformed to the standard system. The 1986 visual data points are marked by short vertical lines and connected by a smooth curve. Those of Lamontagne et al. are connected by a dotted curve. There are a few remarkable phenomena in Fig. 1, which we shall discuss briefly:

1. The light curve of 1986 is different from the light curves of 1980 (Cherepashchuk 1981) and 1985 (Lamontagne et al. 1986), but still shows one high and two low maxima (see also Sect. 4). The phase difference between the previous (1980–1985) and present (1986) highest estimated maximum is  $\sim 0.35$ . The phase coverage for the two lower maxima is insufficient to verify this. Also the polarimetric curves of 1986 made from 24 February–6 April 1986 (thus partly simultaneous with our photometry) differ appreciably from those made in 1985 (Moffat et al. 1986). A further study on the long term stability of the light curve and polarization and on the possible existence of a secondary period (Gosset and Vreux, 1987) would be highly desirable.

2. No epoch-dependent light curve shows any significant intrinsic scatter about a sample curve (i.e. scatter  $< 0^m005$ ), contrary to most of the light curves of other variable WR stars.

3. The colour curves  $B - L$ ,  $B - U$ , and  $U - W$  are clearly variable, with the largest amplitude in  $U - W \sim 0^m013$ . Perhaps this is due to the variability of the strong emission lines in the  $W$  filter ( $\lambda_{\text{eff}} = 3236 \text{ \AA}$ ; see Sect. 4.3), whose relative narrowness

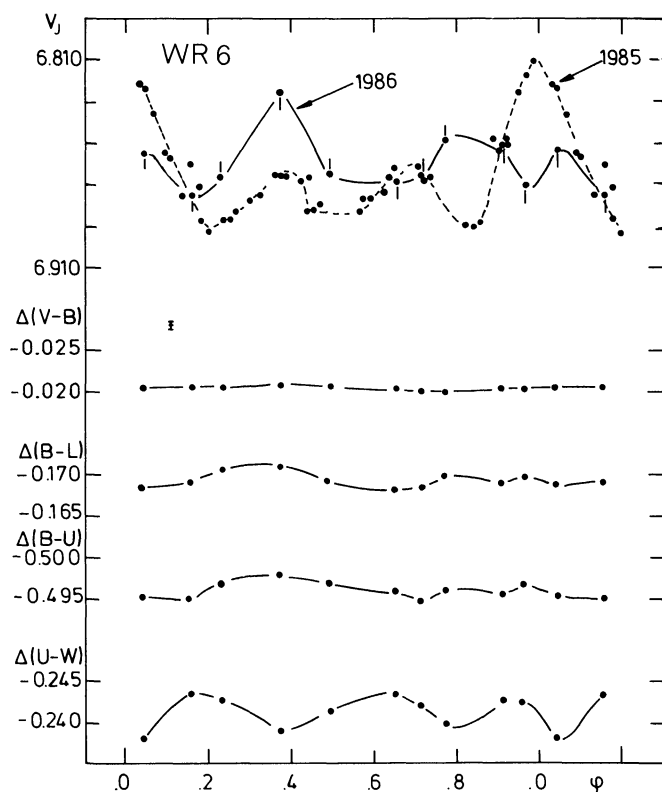
**Table 3.** Average photometric data of program stars in the *VBLUW* system and the *UBV* system (with subscript J) and their standard deviations

WR/HD Name	Spectral type <sup>a,b</sup>	$P^b$ (days)	$V$					$V_J$ (mag)	$(B - V)_J$ (mag)
			$V$	$V - B$	$B - U$	$U - W$	$B - L$		
			(log intensity)						
WR 6/50896 EZ CMa	WN 5(SB1)	3.763	0.0107 $\pm 0.0050$	-0.0152 $\pm 0.0015$	-0.0612 $\pm 0.0010$	-0.1331 $\pm 0.0021$	-0.0078 $\pm 0.0016$	6.859 $\pm 0.013$	-0.049 $\pm 0.004$
WR 16/86161	WN 8 <sup>c</sup> (SB1)	10.73	-0.5676 $\pm 0.0065$	0.1581 $\pm 0.0015$	0.0515 $\pm 0.0014$	0.0505 $\pm 0.0013$	0.0423 $\pm 0.0019$	8.292 $\pm 0.016$	0.373 $\pm 0.004$
WR 22/92740	WN 7 + abs (SB1)	80.35	0.1939 $\pm 0.0032$	0.0595 $\pm 0.0007$	-0.0198 $\pm 0.0006$	0.0106 $\pm 0.0009$	0.0069 $\pm 0.0019$	6.396 $\pm 0.008$	0.139 $\pm 0.002$
WR 24/93131	WN 7 + abs		0.1564 $\pm 0.0038$	0.0124 $\pm 0.0006$	-0.0557 $\pm 0.0007$	-0.0118 $\pm 0.0009$	-0.0158 $\pm 0.0017$	6.493 $\pm 0.010$	0.022 $\pm 0.002$
WR 25/93162	WN 7 + abs		-0.4929 $\pm 0.0019$	0.1959 $\pm 0.0010$	0.0379 $\pm 0.0010$	0.0485 $\pm 0.0015$	0.0485 $\pm 0.0018$	8.103 $\pm 0.005$	0.458 $\pm 0.003$
WR 40/96548	WN 8(SB1)	4.1584	-0.3263 $\pm 0.0128$	0.0861 $\pm 0.0017$	0.0207 $\pm 0.0023$	0.0168 $\pm 0.0024$	0.0145 $\pm 0.0028$	7.694 $\pm 0.032$	0.204 $\pm 0.004$
WR 90/156385 <sup>c</sup>	WC 7		-0.0229 $\pm 0.0021$	0.1294 $\pm 0.0014$	0.0718 $\pm 0.0013$	-0.0036 $\pm 0.0013$	0.0697 $\pm 0.0028$	6.933 $\pm 0.005$	0.307 $\pm 0.004$

<sup>a</sup> Spectrum from the catalogue of van der Hucht et al. (1981)

<sup>b</sup> Binariness and period from the review of Hidayat et al. (1984)

<sup>c</sup> Non-variable star (see Table 2c)



**Fig. 1.** Top: The dashed line represents the  $V_J$  light curve of WR 6 = EZ CMa = HD 50896 for 1985 (Lamontagne et al., 1986). The solid line represents the  $V_J$  light curve for 1986 (this paper: our data points are marked with short vertical lines).  $V_J$  means the  $V$  of the *UBV* system in magnitude scale. Below: the colour curves relative to the comparison star in log int. scale

would even enhance the effect compared to the other broader filters. Although our data points cover three cycles only, these colour curves suggest the presence of *phase dependent colour variations*, especially the colour curve in  $U - W$ . More accurate observations are necessary to confirm this.

4. The colour curves  $B - L$  and  $B - U$  go in phase with each other, while  $U - W$  goes in antiphase. Figure 2 shows the correlation diagram of relative brightness against relative colours. It suggests that  $B - L$  and  $B - U$  become bluer with increasing brightness, although the number of observations is still too low to be completely convincing.  $U - W$  shows the opposite behaviour. The absence of any significant variation in  $V - B$  is in contrast with, for example,  $V - B$  of the WC 9 star WR 103 = HD 164270 (Paper I), where this colour becomes bluer with increasing brightness.

The fluxes in the  $L$  and  $U$  bands have the largest range, that in  $W$  has the smallest of the five passbands. If for example the continuum varies more strongly than the strong He II 3203 Å line (see Table 5), then this could explain the reduced  $W$  amplitude. Moffat (1983) has observed the same trend of the He II 4886 Å line in the star HD 96548.

According to its position in the two-colour diagrams (Fig. 9, Sect. 4.2) WR 6 shows at present a strong excess in the  $W$  band ( $\lambda_{\text{eff}} = 3236 \text{ \AA}$ ) by  $\sim 0^{\text{m}}25$ . This will be discussed in Sect. 4.3.

### 3.2. WR 16 = HD 86161

This object, of spectral type WN8, shows photometric and radial velocity variations which Moffat and Niemela (1982, hereafter called MN) have interpreted as being caused by a binary configuration with a period  $P = 10^{\text{d}}73$ . The double waved light curve, likely being caused by the distorted WR star, shows a large intrinsic scatter of nearly half of the total amplitude, i.e.  $\sim 0^{\text{m}}03$ , which most likely originates in the WR star. That the WR star might be distorted is supported by the colour curves of MN, which become bluer when the star is brighter.

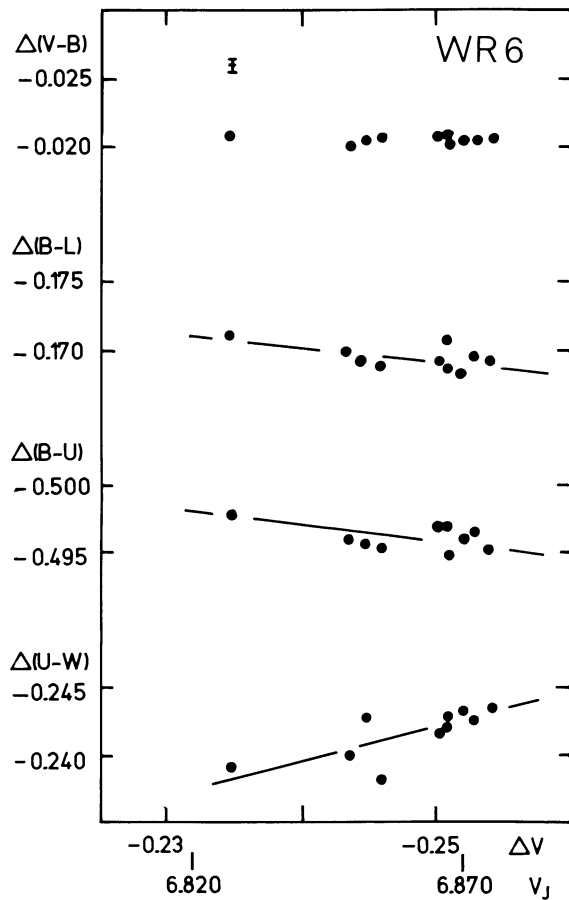


Fig. 2. Colours versus brightness (and  $V_j$ ) of WR 6. (Bright is to the left and blue is up)

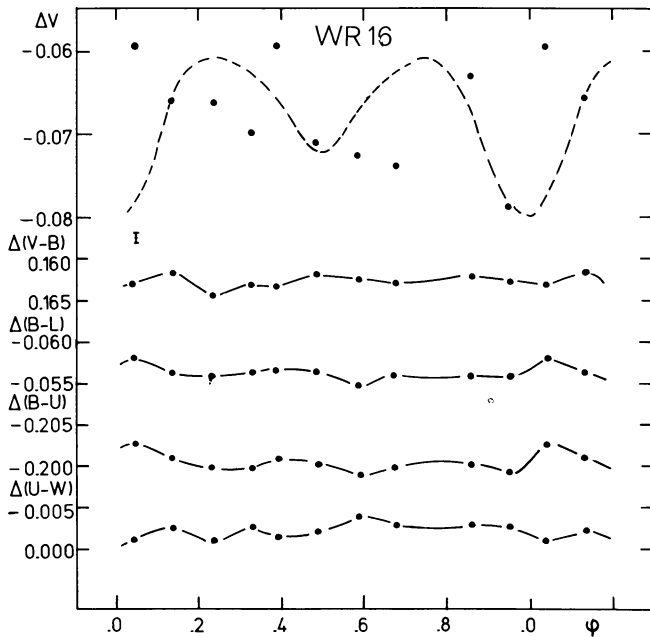


Fig. 3. The phase diagram for the relative brightness and colours of WR 16 = HD 86161. The light curve of Moffat and Niemela (1982) is roughly sketched through our visual data points

A faint optical red companion at a separation of  $\sim 8''$  from WR 16, lies just inside our diaphragm after slightly decentering the program star. However, the s.d. of the relative brightness in the first two nights, appeared to be about a factor two larger than in the other nights, viz.  $\pm 0.0020$  (log int). Apparently the position of the optical companion was then close to the edge of the diaphragm. Precise photometric parameters for this star are:  $V_j = 11.79$  and  $(B - V)_j = 0.90$ , in excellent agreement with the values given by MN. The star is presumably a reddened main sequence star of an early G type with  $E(B - V) \sim 0.35$ .

Figure 3 shows the phase diagram of light- and colour variations. The phases were computed with the ephemeris of MN for zero phase (primary minimum):

$$\text{J.D. } 2442456.44 + 10.73\text{E}$$

Because of the large intrinsic scatter around the mean light curve of the potential binary revolution and the small number of our observations, it is impossible to check whether the ephemeris needs any correction. Therefore only a rough representation of the double wave is sketched through our visual data points.

Since our observations only cover just one cycle it is also impossible to establish if phase dependent colour variations exist. All colour variations are of the order of  $0^m.01$ . A smooth line connects all data points in order to illustrate the variations more clearly.  $B - L$  and  $B - U$  vary in phase with each other and become bluer with increasing brightness, while  $U - W$  shows

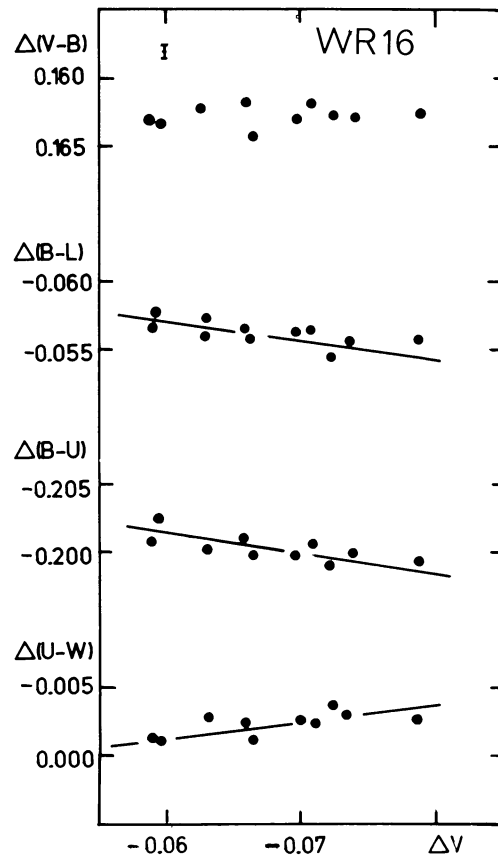


Fig. 4. Colours versus brightness of WR 16 = HD 86161. (Bright is to the left and blue is up)

the opposite behaviour by roughly the same amount. Thus the flux in the  $W$  band varies more synchronously with those in the  $V$  and  $B$  bands, while the fluxes in the  $L$  and  $U$  bands vary more strongly.

Figure 4 illustrates these facts once again in the correlation diagrams. The colour variations found by MN show the same correlation between brightness and colours. However the range of our colour variations is  $\sim 4$  times smaller than theirs, presumably caused by the small number of our data points and the higher accuracy. Nevertheless the small scatter around the average correlations is surprising since we are supposedly dealing with two kinds of light variation: one caused by the alleged binary revolution and one by the intrinsic random scatter. More observations are necessary to investigate this further.

### 3.3. The three WR stars in the Carina nebula

#### 3.3.1. WR 22 = HD 92740

WR 22 is a WN7 +  $a$  type star and has a binary period  $P = 80^d.34$  according to its radial velocity variations (Moffat and Seggewiss, 1978; Conti et al., 1979; Niemela, 1979). The same comparison star has been used as for the other two stars WR 24 and WR 25.

The phase interval of our observations lies between  $\phi = 0.03$  and 0.17 if we use the time of periastron passage as the zero point:  $T_0 = \text{J.D. } 2440728.9$ .

Figure 5 (left panel) shows the light- and colour curves as a function of the Julian Date. Apart from the presence of erratic

micro-variations in the visual with a range of  $\sim 0^m.02$  and a time scale of  $\sim 1$  day, no detectable colour variations are present (cf. light and colour curves of Moffat and Seggewiss, 1978).

#### 3.3.2. WR 24 = HD 93131

WR 24 is a WN7 +  $a$  type star and probably a single object (Moffat and Seggewiss, 1978), although some random fluctuations may be present in the radial velocity (Conti et al. 1979).

Figure 5 (middle panel) also shows erratic continuum fluctuations with a range of  $\sim 0^m.025$  and a time scale of  $\sim 1$  day (Moffat and Seggewiss, 1978 did not find any photometric variations). Colour variations are absent beyond the maximum mean error.

#### 3.3.3. WR 25 = HD 93162

Similar to WR 22, WR 25 is a WN7 +  $a$  type star with some random fluctuations present in its radial velocity (Moffat, 1978; Conti et al, 1979). Fitzpatrick (1982) reports narrow absorption lines of Fe v and O v in WR 25 as well as in WR 140 = HD 193793. In the meantime, Williams et al. (1987) discovered that WR 140 is an eccentric, long-period binary (WC7 + O4,  $P = 7.9$  yr), which explains the absorption lines and all its variations at X, UV, optical and IR wavelengths. It is very well possible that also WR 25 is a long period (WN7 + O) binary, with its absorption lines originating in the O-type companion and its anomalously strong X-ray flux (Sanders et al., 1985) originating in the colliding winds during periastron. It is also possible that WN7 + abs.

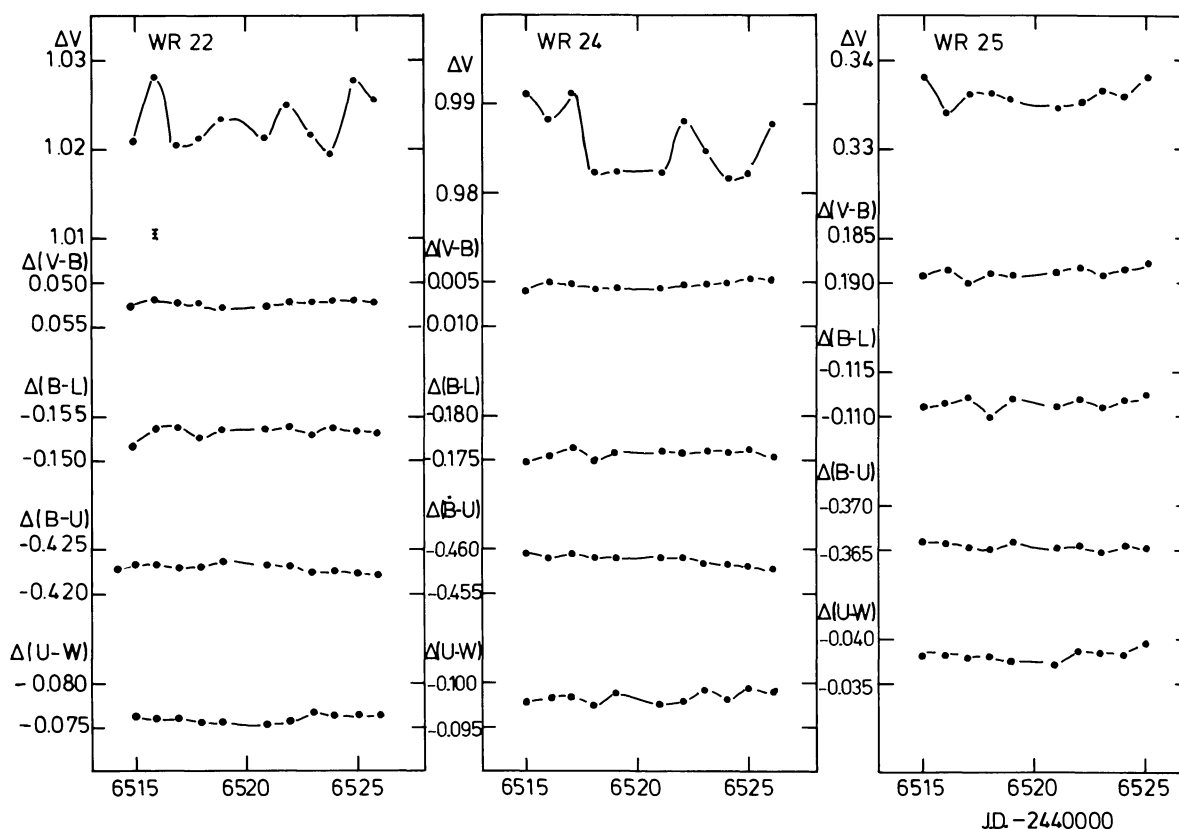


Fig. 5. The light- and color curves of the three WR stars in the Carina Nebula (WR 22 = HD 92740, WR 24 = HD 93131 and WR 25 = HD 93162) relative to a common comparison star

**Table 4.** Standard deviations for each of the nightly averages  $V$  of the  $VBLUW$  system of the comparison star HD 93712 and the three WR stars WR 22, 24 and 25 (in units of  $0.0001 \log$  intensity scale). The numbers on top of the columns are the brightness  $V$  in the Walraven system and the magnitude  $V_j$  in the  $UBV$  system

Star	HD 93712	WR 22	WR 24	WR 25
$V$ (log int)	-0.8293	0.1939	0.1564	-0.4929
$V_j$ (mag)	8.958	6.396	6.493	8.103
J.D.-				
2440000				
6515.753	7	7	7	5
6516.618	9	7	9	5
6517.726	13	9	4	10
6518.726	8	8	10	9
6519.708	7	5	7	6
6521.681	11	8	6	3
6522.674	5	7	11	8
6523.653	13	5	9	13
6524.712	26	15	21	27
6525.722	4	5	6	7
6526.771	10	6	9	9

stars are more Of-like, with a higher ratio of H/He and visible photospheres.

Figure 5 (right panel) shows continuum variations which are a factor 3 to 4 smaller than in the cases of WR 22 and WR 24, with a range of  $\sim 0^m01$  and the absence of any significant colour variations.

Since these three stars were measured alternately with the same comparison star, which lasted a total of about 50 min (Sect. 2), the s.d.'s of the nightly photometric averages can be compared with each other and with those of the comparison star, to search for short time scale variations. Table 4 lists the s.d.'s of the visual brightness. It is obvious that the three WR stars do not show any sign of such a variation above the  $\sigma = 2.5\%$  level (or  $0.0010 \log$  int.). Because of atmospheric fluctuations the s.d.'s at J.D. 2446524.7 are largest. Moffat and Haupt (1974) did not find short-period variations above the 1% level in some other WR stars.

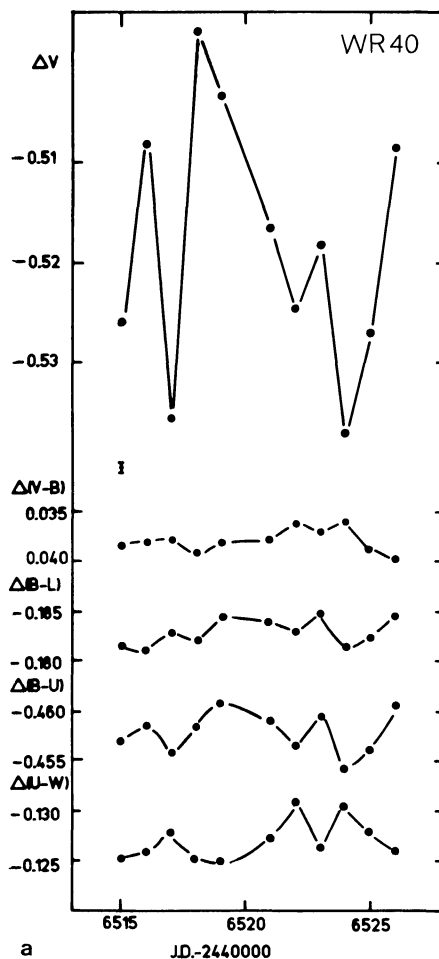
#### 3.4. WR 40 = HD 96548

This WN8 star is, according to Moffat and Isserstedt (1980, hereafter MI), a member of a binary with  $P = 4^d762$  or  $2^d381$ . Moffat (1983) revised the period down to  $4^d158$  (but other periods between  $4^d$  and  $5^d$  fit the data fairly well too) on the basis of new radial velocity observations. However, Smith et al. (1985) reanalysed all previously published photometry and found as the best period  $5^d879$ , while the previous periods only appear as weak signals in the power spectra. The double waved light curve (see Fig. 8 in MI and our Fig. 6b) using the first period above, shows a maximum amplitude of  $\sim 0^m1$ , and considerable intrinsic scatter of nearly the same range. A similar picture is obtained with the other periods. Variations of  $\sim 0^m02$  occur during the 1976 observations of MI. MI's colour curve, a pseudo  $B - V$  curve, runs in antiphase, which is *opposite* to what one expects for hot stars distorted by the presence of a nearby companion, such as the

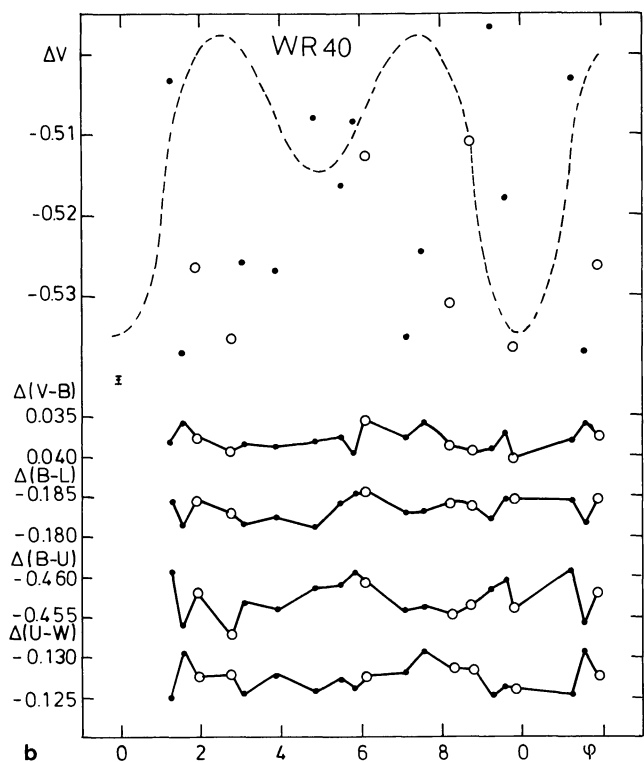
WN8 star WR 16 (cf. Moffat and Niemela 1982 and Sect. 3.2). Because of the large intrinsic scatter, one needs many observations well spread over time, in order to have any success with period search programs. Moffat et al. (1987) could not find any convincing period in their linear polarization variations based on fourty observing nights.

Because this star poses a challenge to us also, as will be explained below, we first show in Fig. 6a the light and colour curves for the observations of March/April 1986 as a function of Julian Date. The total light amplitude is similar to that of MI and the shape of the curve is like most of MI's observations, if plotted against the Julian Date. Also the anticorrelation between  $V$  and  $V - B$  is more or less in agreement with their results, but again with a much smaller range, viz.  $\sim 0^m01$  instead of  $\sim 0^m03$ .  $B - L$  and  $B - U$  vary in phase with each other and in antiphase with  $U - W$ , a behaviour we also have seen in the WR stars WR 6 and WR 16 (Sects. 3.1 and 3.2, respectively).

Figure 6b shows the phase diagram for  $P = 4^d762$ . Since we cannot refine MI's period nor their zero point (J.D. 2442000.0), we only sketched roughly MI's double wave through our visual data points. The extra observations from Houtekamer and Röttgering are added as circles. The data points of the colour curves are connected by solid lines, illustrating the erratic nature (see also the scatter in Fig. 7). It is obvious that there is little



**Fig. 6a.** The relative brightness and colours of WR 40 = HD 96548 as a function of Julian Date



**Fig. 6b.** The phase diagram for the relative brightness and colours of WR 40. The light curve of Moffat and Isserstedt (1980) is roughly sketched through our visual data points

support or the proposed period. The same is true for the other periods. Of course this could be credited to the large intrinsic scatter, but it is also possible that all the periods are spurious.

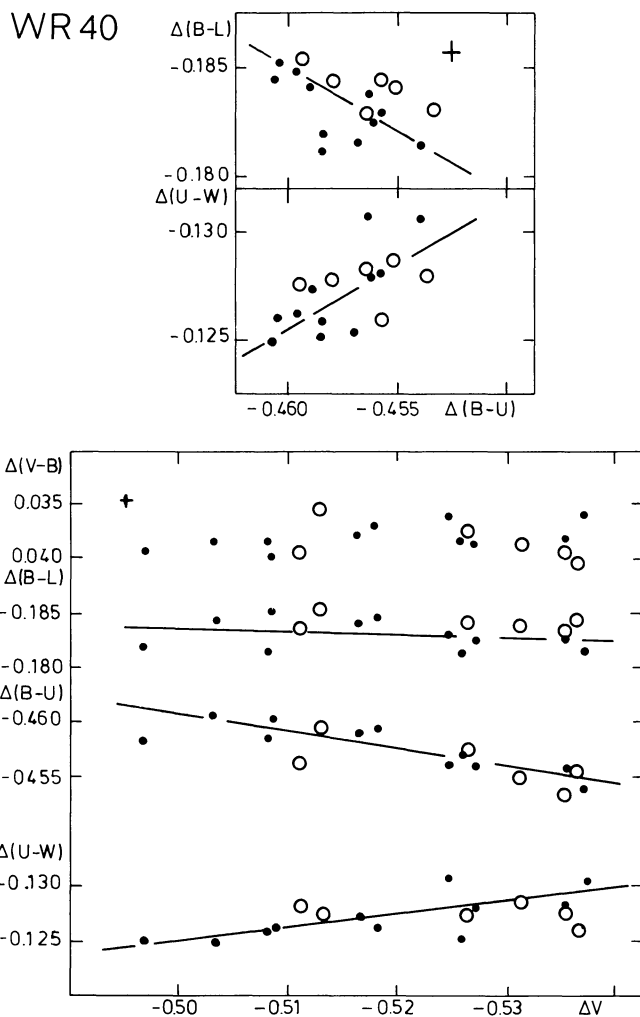
As a matter of interest we analysed the 1975 and 1976 visual observations of MI with the period search program of Sterken (1977). This method determines the optimal characteristic time scale (or period) by a method of least squares harmonic fitting. We found several possibilities within the interval  $2-10^d$  with interval steps of  $0^d01$ :

1.  $P = 2^d37$  with a correlation coefficient  $r = 0.42$  only. This period is thus in accordance with the one found by MI with the Lafler-Kinman method, which they then doubled to yield a final estimate.

2.  $P = 5^d88, 5^d96$  and  $6^d05$  with correlation coefficients  $r = 0.495, 0.503$  and  $0.505$  respectively, thus only marginally better than the previous period. The first period is thus equal to the one found Smith et al. On the face of it, a period of that length fits the light curve in Fig. 6a better, and also the photometric and radial velocity data of MI, if plotted against the Julian Date. However, the phase diagrams are, as expected, not much better than any of the other ones. Thus the problem with the period is in our opinion not yet settled, if the existence of a double mode can be confirmed at all.

Figure 7 shows the correlation of relative brightness with relative colours and the correlations  $\Delta(B-U)/\Delta(B-L)$  and  $\Delta(B-U)/\Delta(U-W)$ . The inverse behaviour of  $V-B$  with  $V$  is obvious, while the other correlations are similar to those displayed in Figs. 2 and 4, but the scatter is sometimes three or more times larger than the maximum value of the m.e. ( $=s.d./\sqrt{n}$ ).

It is of interest to note that the correlations displayed in the top part of Fig. 7 are similar to those for the micro-variations



**Fig. 7.** Colours versus colours (at the top) and colours versus brightness of WR 40. (The scale of the first mentioned diagrams is twice that of the other diagrams)

of some of the highly luminous O type stars, where density and temperature variations are supposed to occur in certain areas of the atmosphere or photosphere through turbulence or shock wave effects etc., and on a similar time scale of  $\sim 1^d$  (van Genderen 1985, 1986).

### 3.5. WR 90 = HD 156385

This single star of spectral type WC 7, is the only WC type star in our sample. According to Davis et al. (1981) the star is constant in light and radial velocity, and according to Moffat et al. (1986) the linear polarization also shows no sign of variability. However, Weller and Jeffers (1979) detected a variation in the strength of the emission line of C IV 4438 Å (situated in our B band), while the C III line at  $\lambda = 4650$  Å was constant. Since the first one only varied marginally, little or no effect on the B brightness is expected.

Figure 8 confirms these findings. The comparison star is variable especially in  $B-L$  and  $B-U$  as has been discussed in Sect. 2. Thus the wavy pattern exhibited by the visual light curve with an amplitude of  $\sim 0^m003$ , if real, is likely due to the comparison star.

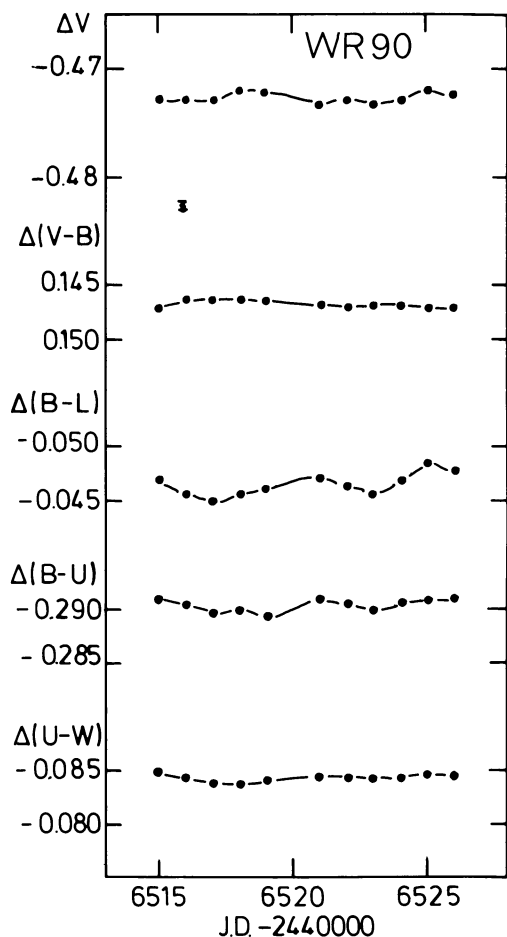


Fig. 8. The relative brightness and colours of the non-variable WR star WR 90 = HD 156385 as a function of Julian Date. The detectable variation in  $B - L$  and  $B - U$  is due to the variability of the comparison star HD 156293 (see Table 1 and Sect. 2)

#### 4. Discussion

##### 4.1. The continuum variability

Theoretical models of WR stars indicate that short time scale oscillations should exist with  $P < 1$  hour (Maeder 1985). So far these oscillations are suspected to cause the rapid X-ray variability of WR 6 by modulating the shocks in the wind (White and Long, 1986), but they are not yet found in the optical (cf. Sect. 3.3; Moffat and Haupt, 1974; Vreux, 1987). The reason must be sought in the presence of the optically thick expanding envelopes, which prevents us from seeing the stationary stellar layers below (see below). However, some activity in a number of spectral features within one night were found, for example in WR 6 (Weller and Jeffers, 1979; Ebbets, 1979; Willis et al., 1986a), or within a few days like in WR 40 (Smith et al., 1986), but there the cause is probably the wind. Apart from that, many WR stars turn out to be variable in brightness, with small amplitudes,  $< 0^m1$ , of which the cause is usually dominated by binary orbit modulation and random intrinsic variations of the wind properties (cf. Moffat and Shara, 1986).

The main purpose of this high precision photometric investigation was to investigate the micro-variations superimposed on the light curves of WR binaries, to search for micro-variations

of single WR stars and to search for any colour variation correlated with the light variation, whether they are caused by orbital revolution or by random variations. The photometric precision so far reached in the literature is of the order of  $\sigma \sim 0^m005$  (Moffat and Shara, 1986). It was our intention to lower this to  $\sigma \sim 0^m002$ , which has in fact been reached. More observations are planned to increase the quantity of data.

The present program consists of six variable WN type stars, of which four are known in the literature as possibly single-line spectroscopic binaries and two are presumably single. The 7th star is of type WC and is also single. This one is the only non-variable object in our sample.

As long as the light variations have amplitudes  $\leq 0^m03$ , colour variations are difficult to detect. If the amplitudes are larger, whether they are caused by binary modulation or by random processes, then variations in  $B - L$ ,  $B - U$  and  $U - W$  in particular, are easily detectable. These amplitudes are often of the order of  $0^m01$ , usually a factor 5–10 smaller than the light variations. The  $B - L$  and  $B - U$  curves vary always in phase with each other, whether we are dealing with binary modulation without intrinsic scatter (like the case of WR 6) or binaries with large intrinsic scatter (like WR 16 and WR 40). In the case of the WC 9 star WR 103, the variations are strongest in the  $U$  and  $B$  bands (Paper I).

In order to make an objective assessment of the contributions of emission lines to the observed photometry, we list in Table 5 observed lines with  $W_\lambda > 0.5 \text{ \AA}$  and lying just within the limits of the Walraven passbands (band widths FWHM from de Ruiter and Lub 1986). It appears that most of the emission lines contribute together  $\leq 10\%$  of the total radiation received in the band-passes  $W$ ,  $B$  and  $V$ . In  $L$  and  $U$  their contribution is much smaller  $\leq 3\%$ . Hence only if the continuum is constant and these lines double their strengths or disappear, which has never been observed, would the brightness variations amount to  $\leq 0^m1$  in  $W$ ,  $B$  and  $V$  and  $\leq 0^m03$  in  $L$  and  $U$ . A few exceptions to the first mentioned rule are for example the He II 3203 Å line in  $W$ : 53% (WR 6), the He I 3188 Å line in  $W$ : 57% (WR 6), 14% (WR 22), 30% (WR 24) and the He II 5412 Å line in  $V$ : 12% (WR 6). For these quantitative estimations we used the precise response curves of the  $VBLUW$  system derived by Lub and Pel (1982).

The important question then becomes whether the observed variations in brightness and colours in the Walraven bands are caused by continuum or line variations. As far as we have searched the literature, on the relatively short time scale ( $\sim 10$  days, like our data set), changes in profiles have been observed (see references at the beginning of this section), but not so much in the equivalent width  $W_\lambda$ . The exceptions found so far are WR 6 where Singh (1984) reports variations in the observed strengths of different emission lines within 1.5 hours and Shylaja (1986a,b; 1987) reports variability in the flux contained in the He II 4686 Å line of WR 6 and CQ Cep. For WR 6 the variability as found by Shylaja is more or less phase dependent, but the curve shows large scatter. The total range of the variation is roughly a factor 1.5 of the minimum flux. The He II 4686 Å line of WR 6 has an equivalent width of 200 to 300 Å (Table 5) and thus contributes 5 to 8% to the flux of the  $B$  band, which is equivalent to  $0^m05$  to  $0^m08$ . A variation in the flux of this line by a factor 1.5 should thus cause a variation in the  $V - B$  colour index by a few hundredths of a magnitude, provided that the prominent He II 5411 Å line is the  $V$  band stays constant (its total contribution there is  $0^m12$ ). However, the  $V - B$  curve in Fig. 1 does not show any

**Table 5.** Equivalent widths of strong emission lines for a number of WR stars in the VBLUW passbands. For comparison we have added some other stars to our program stars.

Walraven filter	$\lambda_e(\text{\AA})$	Emission lines	$W_\lambda(\text{\AA})$											
			WN 5	WN 7			WN 8			WC 7				
			WR 6	WR 22	WR 24	WR 25	WR 78	WR 16	WR 40	WR 156	WR 57	WR 90		
<i>W</i>	3236 (157)	He I He II	(1) (2) (3)	(1) (3) (3)	(3) (3) (3)	(3) (2) (2)	(2) (3) (3)	(3) (3) (3)	(2) (2) (2)	(1) (1) (1)	(4) (4) (4)	(4)	64*	
			130*	14*	24*	35*	5.8							
<i>U</i>	3623 (232)	He I C IV C III He I C IV	3188* 3203	3614,34 3690 3704 3705 3720			1.0	0.8				17.3 9.4 37.2		
<i>L</i>	3837 (221)	C III He I C IV N IV/III O III H I O IV He I O IV H I He II He I He II C IV N III			7.2		3.1					17.3 9.4 37.2	13.8 18.2 8.5	
							0.04							
							0.8 0.7							
							3.5 0.6			22.9	32.4	15.1		
			8.8 3.5	8.5 4.0						0.7	27.4			
										1.9				
<i>B</i>	4298 (423)	Si IV He II N III Si IV C III/O V He I C III C III He II C IV	4089 4099 4100 4116 4122 4144 4156 4187 4200 4217											
							2.1 0.6 1.2					14.0		
			37.7	46.4			5.9 3.4					18.7		
													7.4 5.2 6.4 8.9	
			19.5	20.4	10.0	P	0.6	0.9	a	2.0	2.3	2.1		

Table 5 (continued)

Walraven filter	$\lambda_c(\text{\AA})$ (FWHM)	Emission lines	$W_\lambda(\text{\AA})$											
			WN 5	WN 7			WN 8			WC 7				
			WR 6	WR 22	WR 24	WR 25	WR 78	WR 16	WR 40	WR 156	WR 57	WR 90		
			(1)	(1)	(3)	(3)	(2)	(3)	(3)	(2)	(1)	(4)	(4)	
		C IV										16.2		
		C II									19.3			
		C III									20.4			
		C III							0.4					
		He II	21.5	19.7	10.7	2.8	1.3	1.4	4.0	7.9	8.3	8.1	23.9	
		N III						1.0				1.1		
		C III												
		C IV						1.4			3.4			
		He												
		C III												
		He II											15.55	
		N III				(6.7)	4.7	11.7	6.3	1.9	19.4	27.5	28.2 (20.9)	
		He II	>200	302	224	18.3	26.3	26.3	5.4	36.9	30.9	25.7	23.3	
V	5441	He II	45.1	61	60.3	1.6	2.5	3.5	0.3	9.1	3.2	6.2	21.9 25.7	
	(708)	C IV											31 33.9	
		O V											25 39.8 25.1	
		C III											450: 416.9	
		C III											475: 436.5	
		C IV												

Notes:

\* He I 3188 for all cases from Willis et al. (1986b)

(1) Smith (1955): observations in 1952–1954

(2) Smith and Kuhi (1981): observations of WR 6 in 1967–1968

(3) Conti et al. (1983): observations  $\pm$  1976

(4) Torres (1985): observations 1978–1981

P: P Cygni emission + absorption

a: absorption

variation larger than  $0^m002$  within the time interval of eleven days, i.e. three cycles! Thus, one is obliged to assume that the He II line in the  $V$  band varies simultaneously with the He II line in the  $B$  band and by the same amount. Simultaneous photometry and spectroscopy would be highly desirable to check this. The fact that the brightness variations (thus also the intrinsic noise) in the five Walraven band-passes vary nearly coherently, despite the enormous differences in emission line content, strongly suggests continuum variations as the main cause. This is thus in accord with the conclusion of Moffat and Isserstedt (1980) and Moffat and Shara (1986).

It can be deduced from the present material that the colour variations caused by binary revolution and those caused by random variations, have apparently more or less the same characteristics in view of the small dispersion around the lines drawn in the scatter diagrams, especially as seen in Figs. 2 and 4. Furthermore, the colour variations are of a nearly similar character for three different WR stars (WR 6, WR 16, and WR 40); see Figs. 2, 4 and 7. An important similarity is that the  $L$  and  $U$  fluxes vary most strongly: 10–20% more than the others. Thus the  $B - L$  and  $B - U$  colours become bluer with increasing brightness. In the case of temperature variations only, one would expect the largest fluctuation for the  $W$  flux. In fact the  $W$  flux varies often less than those in  $L$  and  $U$  (a possible explanation is given in Sect. 3.1) and this is also the case for some highly luminous O type stars, which also show optical micro-variations (van Genderen 1985, 1986). More observations are necessary to try to differentiate between the colour variations of the binary revolution and the light variations superimposed thereon. The fact that the three stars mentioned above have different relative line strengths and that the  $L$  and  $U$  bands are by far the least influenced by emission lines, but yet vary most strongly, suggests that the colour variations, at least in part, are also caused by continuum variations.

Although the variation in  $W$  is smaller than in  $U$  and  $L$ , we believe that small temperature effects in the pseudo-photosphere are the cause of the continuum variations. In this context it is worthwhile to consider what the extended dense winds of WR stars do dynamically. Is differential rotation triggered by the underlying rotating star, causing an intricate pattern of turbulence? Results of such turbulence could be the vertical expulsion of hot blobs or the presence of eddies with a certain lifetime. In an eddy one can look further into the hotter and denser parts of the envelope. That WR stars may rotate fast has been claimed by Massey and Conti (1981) who found for the single WN3 + abs. star WR 3 (=HD 9974) that  $v \sin i = 150\text{--}200 \text{ km s}^{-1}$ , assuming that the absorption lines do really originate in the WR star (if they do, in that case one would have to explain the anomalously high ratio of H/He in the wind). Poe and Friend (1986) have suggested that in order to produce the observed mass loss rates and velocity laws of WR stars, the underlying star should rotate at nearly 90% of the break up velocity. On the other hand, with the new high  $T_{\text{eff}}$  values (see Sect. 4.2), radiation pressure will work easily and the rotation would be a secondary effect.

#### 4.2. The colour-colour diagrams

Figure 9 shows the three two-colour diagrams. As a comparison the  $(B - V)_J$  scale is also indicated at the bottom of the figure. The smooth curves and the arrows represent the main sequence and the reddening line for hot stars, respectively.

The five comparison stars (dots) are also plotted. They have

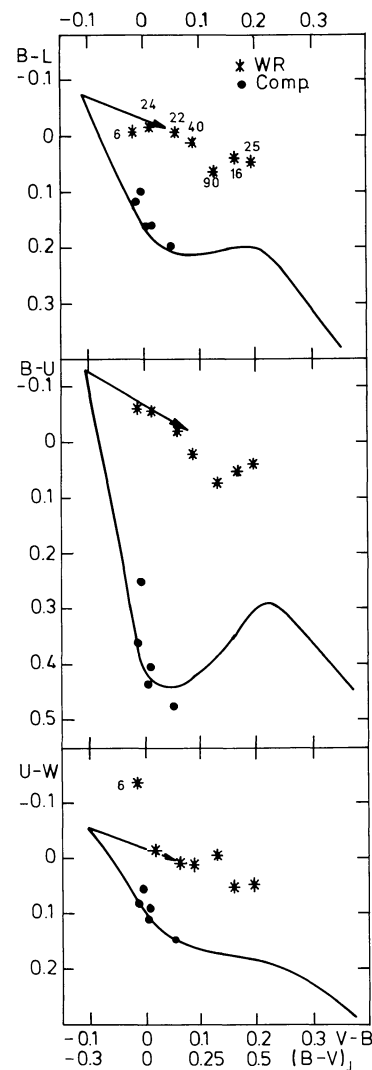


Fig. 9. The three two-colour diagrams for the comparison stars (dots) and WR stars (asterisks). The  $(B - V)_J$  scale is also indicated

suffered little or no interstellar reddening. HD 50853, of which the luminosity class was unknown, is also a main sequence star (Table 1) in view of its position in Fig. 9.

Hot stars with  $T_{\text{eff}} \gtrsim 30000 \text{ K}$  should lie at the top of the main sequence, if unreddened. Theoretical models of quasi-homogeneous stars near the helium sequence such as is often assumed for the Wolf-Rayet stars, have very high temperatures:  $\sim 100000 \text{ K}$  (Stothers and Chin, 1979; Maeder, 1985), but because of their thick extended atmosphere, the photospheres are practically invisible. Thus light is only received from some cooler layer, a pseudo-photosphere, where the envelope becomes optically thick. Temperatures determined by using expanding model atmospheres thus results into values in the range  $20000\text{--}50000 \text{ K}$  (Willis, 1982; Schmutz and Hamann, 1986; van der Hucht et al., 1986).

Also, the comparison of the  $VBLUW$  photometry for 40 WR stars (including the seven program stars) with theoretical reddening-independent colours, based on Kurucz (1979) models computed by Lub and Pel (1982), resulted in temperatures between  $15000\text{--}40000 \text{ K}$  (van Genderen and van der Hucht, in preparation). The average pseudo photospheric temperatures

**Table 6.** “Reddenings” for the WR stars derived from Fig. 9. As a comparison we also show in the last column the  $E(B - V)_J = 1.21 E(b - v)$  derived by Hidayat et al. (1987) from a filter system designed for WN stars (Smith 1968; Lundström and Stenholm, 1979)

WR	$E(V - B)$	$E(B - V)_J$	$E(B - V)_J^H$
6	0.08	0.19	0.04
16	0.27	0.63	0.68
22	0.17	0.40	0.28:
24	0.12	0.28	0.24
25	0.31	0.72	0.68:
40	0.19	0.45	0.51
90	0.22	0.52	0.22

derived from the *VBLUW* photometry appeared to be  $37000 \text{ K} \pm 6000 \text{ K}$  s.d. for the WN stars and  $29000 \text{ K} \pm 6000 \text{ K}$  s.d. for the WC stars. The systematic difference of  $\sim 8000 \text{ K}$  between WC and WN stars could be explained by the fact that the WC stars are more evolved and have denser and more extended envelopes. In any case, the intrinsic position of the WR stars should lie close to or at the top of the main sequence, provided that  $V - B$  is not reddened by a peculiar energy distribution.

According to Fig. 9, all WR stars are displaced to be the right and consequently reddened. Table 6 tabulates the values  $E(V - B)$  and  $E(B - V)_J$ , using the transformation equation from Pel (1982):

$$\frac{E(B - V)_J}{E(V - B)} = 2.39 - 0.17E(V - B)$$

The estimated formal accuracy of  $E(B - V)_J$ , is of the order of  $\pm 0^m04$ , provided that the energy distributions are normal, something that cannot be guaranteed. In fact these photometric reddening estimates probably cannot be trusted, due to the large inconsistencies of the reddening estimates based on the interstellar  $2200 \text{ \AA}$  absorption band and on narrow and other broad-band photometry, with different contributions of emission lines for different methods. Examples are (1) WR 90, for which Smith (1968) finds  $0^m11$ , Willis and Wilson (1977)  $0^m25$ , van der Hucht et al. (1979)  $0^m60$ , Hidayat et al. (1987)  $0^m22$  (transformed from  $E(b - v)$  by multiplying by 1.21) and in the present paper  $0^m52$ ; or (2) WR 6 with  $0^m$  by Smith and Kuhi (1970) and van der Hucht et al. (1979),  $0^m12$  by Holm and Cassinelli (1977),  $0^m04$  by Hidayat et al. (1987) and  $0^m19$  by the present investigation. Those of Hidayat et al. (1987) are based on a filter system especially designed for WN stars, and we list them for all program stars in the last column of Table 6.

#### 4.3. The complex variability and the ultraviolet brightness of WR 6

According to Fig. 9 WR 6 shows an excess in the *W* band ( $\lambda_{\text{eff}} = 3236 \text{ \AA}$ ) with respect to *U* by  $\sim 0.1$  log int. scale, i.e.  $\sim 0^m25$ . Its *U - W* colour is thus quite abnormal, while *B - L* is slightly too red (thus  $L(\lambda_{\text{eff}} = 3837 \text{ \AA})$  is slightly deficient with respect to *B* by  $\sim 0^m1$ ) and *B - U* is more or less normal. The *W* excess is not surprising in view of the fact that the He I 3188  $\text{\AA}$  and He II 3203  $\text{\AA}$  emission lines dominate the radiation in this band. Their equiv-

alent widths (both lines fall well within the filter bandpass) as measured by IUE on January 28, 1979 (Willis et al. 1986b) are together 57% of that of the *W* band. It is unknown what the equivalent widths of these lines were at the time of our observations in 1986, but their presence must have been still conspicuous. It would be of interest to know whether the lines were somewhat fainter in 1986, since the *W* excess should be higher if the strength was the same as in 1979. That the equivalent width  $W_\lambda$  of He lines can vary on a long time scale is another result from Table 5. The three observations of WR 6 listed in Table 5 are separated by approximately 10-year intervals. It appears that the more recent ( $\sim 1976$ ) observations by Conti et al. (1983) for He II 4200, 4339 and 4686  $\text{\AA}$  yield smaller  $W_\lambda$ 's within 30 to 50% of the previous  $W_\lambda$ 's by Smith and Kuhi (1981) and Smith (1955)! However, one should be careful, since most of these  $W_\lambda$ 's are based on photographic spectra and may be not very reliable. In this respect it is of interest to note that another intermediate WN star, WR 138 = HD 193077 (WN 6) also with a suspected low mass companion (Lamontagne et al. 1982) shows variations in  $W_\lambda$  of its emission lines by a factor of 2 on a time scale of one year, for the He II 4686  $\text{\AA}$  emission line even on a time scale of 96 days (Annuk, 1985).

Hillier (1987) has produced model line intensities which vary (directly or indirectly) as a function of several parameters, such as wind temperature, luminosity and mass loss rate. Observations indicate that the envelopes of WR stars are apparently subject to variations in density and temperature on a long time scale ( $\sim$  years). Indeed the visual brightness of WR 6 increased from 1975 to 1977, as we shall discuss later.

With respect to the *W* excess, it is important to mention the result of the ANS observations in the 1550, 1800, 2200, 2500 and 3300  $\text{\AA}$  bands, made in the years 1974–1976 (van der Hucht et al. 1979). Our *W* band lying at the short wavelength side of the ANS band,  $\lambda_c = 3300 \text{ \AA}$ , contains the dominant emission lines He I and He II, while the ANS band has only very little coverage. It is therefore conceivable that the 3300  $\text{\AA}$  ANS band did not show an excess. The 3300  $\text{\AA}$  band even showed some deficiency when compared with a model energy distribution (adopting  $E(B - V)_J = 0$ ). The deficiency becomes even stronger for the shorter wavelengths as shown by van der Hucht et al. and cannot be removed, apart from the 3300  $\text{\AA}$  flux, if a higher reddening is adopted, e.g. like  $E(B - V)_J = 0.12$  (see Sect. 4.2.). They explained the far ultraviolet deficiency with respect to the model atmosphere around 1974–1976 by the presence of a more than normal extended atmosphere, which also could explain the infrared excess.

Perhaps it is not accidental that the star increased its visual brightness from 1975 up to 1977 by  $0^m06$ , while at the same time the variability increased from nearly constant in 1975 to a single wave curve in 1977 (Firmani et al., 1980). In 1980 there were three maxima of which one is high and two are low (Cherepashchuk, 1981), which was still the case in 1985 (Lamontagne et al. 1986). At present (1986) these three maxima have been drifted by  $\sim 0.35$  in phase assuming that the period of revolution did not change (Fig. 1). Because of the use of different visual band-passes or different comparison stars by these authors, it is impossible to verify whether the star's brightness continued to rise after 1977. Since the bright He II line in the *V* band appeared to be constant from 1952/1954 up to  $\sim 1976$  (Table 5) and the visual brightness rise was recorded between 1975 and 1977, we presume that the latter was caused by a continuum change. The brightness decrease

of the He lines in the B band up to  $\sim 1976$  is estimated to amount to only a few percent. It is tempting to suggest a causal connection between all these phenomena. For example: an increase of the transparency of the outer envelope since  $\sim 1975$  could provide us a better view into the hotter layers, so that temperature and visual brightness rose, and according to the model line calculations of Hillier (1987), the He line strengths should then decrease, as is observed (Table 5). Simultaneous spectroscopy and photometry over a period of many years would be very useful.

The hotter pseudo-photosphere ( $T_{\text{eff}} \sim 40000$  K derived from the photometry in conjunction with model atmospheres of Kurucz 1979) is apparently not uniformly illuminated. Semi-stable bright spots, for example places where one can look even further into the hotter layers, such as large semi-stable eddies (see Sect. 4.1), could be the explanation of the three maxima.

That also a strong turbulence exists in the accelerating parts of the wind of WR 6 can be deduced from the rapid phase-independent variations (within a few hours) in the P Cygni profiles of lines such as N IV,  $\lambda = 1718 \text{ \AA}$  (Willis et al., 1986a).

The cause of the intrinsic random light variations in the light curves of the other WR stars with a time scale of  $\sim 1^d$ , must probably also be sought in a dynamically unstable and thus presumably non-uniformly illuminated pseudo-photosphere.

## 5. Conclusions

We have investigated the micro-variations of brightness and colours in the *VBLUW* system of Walraven for seven WR stars within a time interval of 11 days. By studying the precise distribution of emission lines and their strengths in the five band-passes and by searching the literature on spectral line variations, we conclude that continuum variations are the main cause of brightness- and colour variations. Temperature effects in the pseudo-photosphere, from which we receive most of the continuum light, are probably the cause. One should take serious account of the possible presence of hot blobs and/or eddies (in which one can look deeper into the hotter layers) in a turbulent envelope.

The presence of emission lines in photometric band-passes like ours, must be the reason that the photometric reddenings are unreliable.

The fact that several characteristics of WR 6 changed on a time scale of years could be caused by a decrease of the mass loss rate causing an increase in transparency of the envelope.

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