

Long-term photometry of the Wolf-Rayet stars WR 137, WR 140, WR 148, and WR 153 ^{*}

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Abstract. In 1991, a long term *UBV*-photometry campaign of four Wolf-Rayet stars was started using the 60 cm telescope of the National Astronomical Observatory Rozhen, Bulgaria. Here we report on our observational results and discuss the light variations.

The star WR 137 was observed during 1991 - 1998. No indications of eclipses were found, though random light variations with small amplitudes exist, which are probably due to dynamical wind instabilities.

WR 140 was also monitored between 1991 and 1998. In 1993, a dip in the light curve in all passbands was observed shortly after periastron passage, with amplitude of 0.03 mag in *V*. This is interpreted in terms of an “eclipse” by dust condensation in the WR-wind. The amplitude of the eclipse increases towards shorter wavelengths; thus, electron scattering alone is not sufficient to explain the observations. An additional source of opacity is required, possibly Rayleigh scattering. After the eclipse, the light in all passbands gradually increased to reach the “pre-eclipse” level in 1998. The very broad shape of the light minimum suggests that a dust envelope was built up around the WR-star at periastron passage by wind-wind interaction, and was gradually dispersed after 1993.

Our observations of WR 148 (WR + c?) confirm the 4.3 d period; however, they also show additional significant scatter. Another interesting finding is a long-term variation of the mean light (and, possibly, of the amplitude) on a time scale of years. There is some indication of a 4 year cycle of that long-term variation. We discuss the implications for the binary model.

Our photometry of WR 153 is consistent with the quadruple model of this star by showing that both orbital periods, 6.7 d (pair A) and 3.5 d (pair B), exist in the light variations. A search in the HIPPARCOS photometric data also reveals both periods, which is an independent confirmation. No other periods in the light variability of that star are found. The longer period light curve shows only one minimum, which might be due to an atmospheric eclipse; the shorter period light curve shows two minima, indicating that both stars in pair B are eclipsing each other.

Key words: techniques: photometric – stars: binaries: eclipsing – stars: binaries: spectroscopic – stars: circumstellar matter – stars: Wolf-Rayet

1. Introduction

Photometric studies of Wolf-Rayet (WR) stars during the past decades (e.g. Moffat & Shara 1986; Lamontagne & Moffat 1987; van Genderen et al. 1987; Balona et al. 1989; Robert et al. 1989; Gosset et al. 1990; Antokhin et al. 1995; Marchenko et al. 1998a, b) have revealed light variations of several per cent (up to 0.1 mag) on time-scales (typically) of days. WR stars are generally believed to be evolved Population I stars, descendants of Of-type stars (Maeder 1996). They exhibit strong, dense winds (mass loss rates of 10^{-5} to $10^{-4} M_{\odot} \text{ yr}^{-1}$) which, in most cases, hide the stellar surface. The wind-flow is dependent on time. Moffat et al. (1988, 1994) and Robert (1994) discovered the existence of small, outward moving wind condensations, which they called propagating blobs. Unlike most O-type stars, the continuum light of many WR stars originates from a layer in the dense wind ($\tau = 1$), a “pseudo-photosphere” (van Genderen et al. 1987), which could be inhomogeneous because of dynamical wind instabilities. The brightness variations of some WR stars proved to be periodic and are possibly due to binary or rotation effects. Core (photospheric) eclipses as well as atmospheric eclipses have been observed. The latter are characterized by only one V-shaped minimum on the light curve, which is caused by the atmospheric eclipse of an O-type star by the WR star’s extended wind (Lamontagne et al. 1996). Random light variations are common in WR stars and they are often superimposed on the regular (binary) variations, increasing the “noise” and sometimes even totally disturbing the underlying regular light variations. Marchenko et al. (1998b) suggested that random light variations (light scatter) may be caused by short-lived, core-induced, multimode fluctuations, propagating in the wind. Other causes of variability, such as radial pulsations (Maeder 1985) non-radial pulsations (Vreux 1985; Antokhin et al. 1995; Rauw et al. 1996) and axial rotation (Matthews & Moffat 1994) have been proposed for WR stars. Occasional “eclipses” caused by dust formation in late-type WC stars have been studied by Veen et al. (1998).

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^{*} Based on observations collected at the National Astronomical Observatory Rozhen, Bulgaria

Table 1. Summary of data for the program stars. The last two columns contain the emission line-contribution to the colours (Pyper 1966)

WR	HD	Spectral types	Comparison star, HD	Check star, HD	$\delta(B - V)$ [mag]	$\delta(U - B)$ [mag]
137	192641	WC7+abs	192538	192987	+0.07	-0.11
140	193793	WC7+O4-5	193888	193926	+0.05	-0.12
148	197406	WN7+c?	197619	196939	+0.01	-0.01
153	211853	2×WN+O, or WN+O and O+O	211430	— — —	+0.02	-0.02

WR 137 is a well known dust maker (Williams 1997; Marchenko et al. 1999). However little is known about long-term light variations for that star and its binary status is still uncertain. WR 140 is another repeating dust maker (Williams 1997). The orbit is well determined. Because of its high eccentricity ($e = 0.84$) the strongest wind interaction occurs at periastron passage. During the last periastron passage in 1993, WR 140 received much attention and has been studied at different wavelengths from X-ray to radio. However, only a few photometric studies in the optical were carried out so far and the long-term behaviour of that star is not known. Both stars WR 137 and WR 140 are included in the infrared study by Williams et al. (1987a) and reported to have dust shells.

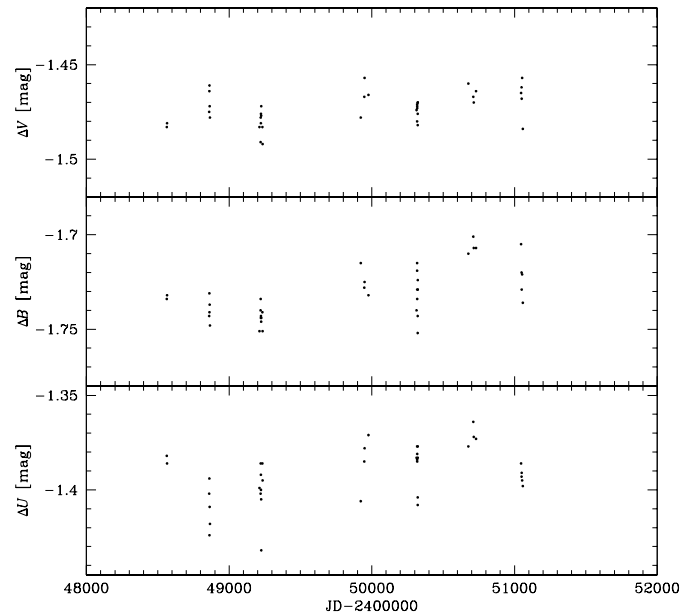
WR 148 is a good candidate for a WR + c (WR plus compact companion) binary. There is some controversy about the light variations concerning the period and the shape of the light curve. Marchenko et al. (1998a) were not able to detect the 4.31 d binary period in the HIPPARCOS photometry data, otherwise well known from ground-based observations (Marchenko et al. 1996). The very “noisy” light curve and unusually broad minimum need further investigation.

WR 153 is a quadruple system (Massey 1981), containing a WN + O and an O + O system, or two WN + O pairs (Panov & Seggewiss 1990). During the past years, several photometric studies have been carried out. Yet the light variability of the two pairs could not always be unambiguously separated (Lamontagne et al. 1996). Our aim is to try to solve some of these controversial questions.

2. Observations

In 1991 we started a long-term photometric study of the four WR stars at the National Astronomical Observatory Rozhen, Bulgaria, using the 60 cm telescope and the UBV single channel, photon counting photometer. The photometric equipment has been used for many years and proved to be very stable (cf. Panov et al. 1982).

Table 1 contains the comparison and the check stars used. Generally, a 20'' diaphragm and an integration of 10 s were used. Each measurement consists of four consecutive integration cycles. An observing cycle was arranged in the following way: Sky - Comp - WR - Comp - Sky and was repeated 3 to 5 times, depending on the quality of the night. A separate measurement of the comparison star against the check star in the same way

**Fig. 1.** Light curves of WR 137 (data from Table 2)

was obtained before or after the WR star observation. Thus a nightly mean was calculated from the 3 to 5 individual measurements. The standard error of the nightly mean is 0.003 - 0.005 mag in most cases. Reduction of the data was made taking into account dead-time effects, atmospheric extinction, and transformation into the standard UBV system. In the following tables we present the magnitudes in the standard system; for WR 137, WR 140, and WR 148 the data are magnitude differences in the sense: comparison star minus WR star. The contribution $\delta(B - V)$ and $\delta(U - B)$ of emission lines to the respective colours are taken from Pyper (1966) and included in Table 1 (last two columns). No corrections have been applied for emission lines in our data. However, it does seem possible to distinguish the continuum light from the emission line variations by comparing the light in the UBV passbands.

Many WR stars show subtle short and long term variations as can be seen in the case of WR 148 (Sect. 3.3). Therefore it is preferable to use the same photometric equipment for long term studies. This reduces possible systematic effects caused by slightly different passbands or response curves.

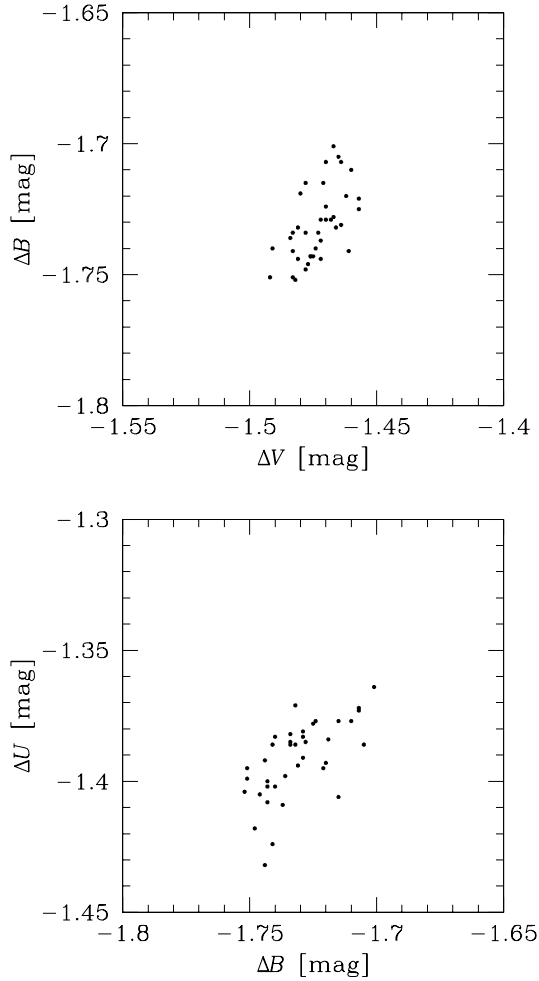


Fig. 2. Random light variability correlations for WR 137 (data from Table 2)

3. Discussion

3.1. WR 137

WR 137 = HD 192641 (WC7 +?) has been studied in the infrared (IR) and peaks in brightness were reported in 1984.5 and in 1997, probably caused by heated dust (Williams 1997). The dust emission has been directly IR-imaged at two epochs recently using the Hubble Space Telescope by Marchenko et al. (1999). The repetition of IR maxima occurs with a ~ 13 yr period, suggesting a possible binary origin, as found for other WR periodic dust makers. WR 137 was discovered to be a spectroscopic binary by Annuik (1995). However, Underhill (1992) did not find any evidence for binary motion in her data. Therefore, the binary status of WR 137 remains uncertain.

Marchenko & Pikhun (1992) published a long-term photometric study for 1958 - 1989, but it is based on photographic plates and the accuracy is insufficient to reveal light variations below a few per cent. Our photometry is presented in Table 2 and the light curves are shown in Fig. 1. We searched for periodicities using the procedure of Lafler & Kinman (1965), in the period range from 1 d to 100 d, but no period could be

Table 2. Differential photometry of WR 137 (= HD 192641) – in the sense comparison star HD 192538 minus WR 137

Year	JD-2400000	ΔV [mag]	ΔB [mag]	ΔU [mag]
1991	48563.225	-1.483	-1.734	-1.382
	48565.229	-1.481	-1.732	-1.386
1992	48860.395	-1.475	-1.743	-1.402
	48861.395	-1.464	-1.731	-1.394
	48862.429	-1.461	-1.741	-1.424
	48863.410	-1.472	-1.737	-1.409
	48865.367	-1.478	-1.748	-1.418
1993	49212.437	-1.483	-1.751	-1.399
	49220.396	-1.491	-1.740	-1.402
	49221.359	-1.478	-1.734	-1.386
	49222.392	-1.481	-1.744	-1.392
	49223.375	-1.476	-1.743	-1.400
	49224.392	-1.477	-1.746	-1.405
	49225.398	-1.472	-1.744	-1.432
	49233.341	-1.483	-1.741	-1.386
	49234.354	-1.492	-1.751	-1.395
1995	49922.475	-1.478	-1.715	-1.406
	49947.449	-1.467	-1.728	-1.385
	49949.428	-1.457	-1.725	-1.378
	49976.379	-1.466	-1.732	-1.371
1996	50313.390	-1.474	-1.740	-1.383
	50317.344	-1.480	-1.719	-1.384
	50317.361	-1.471	-1.715	-1.377
	50318.343	-1.472	-1.729	-1.381
	50318.363	-1.473	-1.734	-1.385
	50321.358	-1.482	-1.752	-1.404
	50321.375	-1.476	-1.743	-1.408
	50322.316	-1.470	-1.724	-1.377
	50322.338	-1.470	-1.729	-1.383
1997	50676.374	-1.460	-1.710	-1.377
	50711.311	-1.467	-1.701	-1.364
	50714.272	-1.470	-1.707	-1.372
	50730.268	-1.464	-1.707	-1.373
1998	51046.379	-1.465	-1.705	-1.386
	51049.343	-1.462	-1.720	-1.393
	51050.331	-1.468	-1.729	-1.391
	51053.334	-1.457	-1.721	-1.395
	51054.310	-1.464	-1.726	-1.386
	51058.364	-1.484	-1.736	-1.398

found. The only photometric variations we can see in our data are random light variations with amplitudes of 0.02 mag (peak to peak) in V during each observing season and up to 0.03 mag (peak to peak) when we compare different years. (However, the peak to peak amplitude from all data is 0.05 mag in B , and 0.07 mag in U .) During 1991-1998 22 measurements of the check star HD 192987 were obtained. The mean values ($N=22$) of the magnitude differences (HD 192538 minus HD 192987) and their standard deviations are $\Delta V = 0.002 \pm 0.008$ mag and $\Delta B = 0.088 \pm 0.009$ mag. The scatter in Fig. 1 is greater than the observational error ($\sim 5\sigma$ in B !) and, therefore, probably contains real erratic variations with small amplitudes.

In 1997, when the last peak in the IR was observed (Williams 1997), no photometric effect can be seen, apart from small-amplitude random variations. Their origin should arise in the continuum, as the plots in Fig. 2 suggest: There are some correlations ($r = 0.58$ for B and V and $r = 0.64$ for U and B)

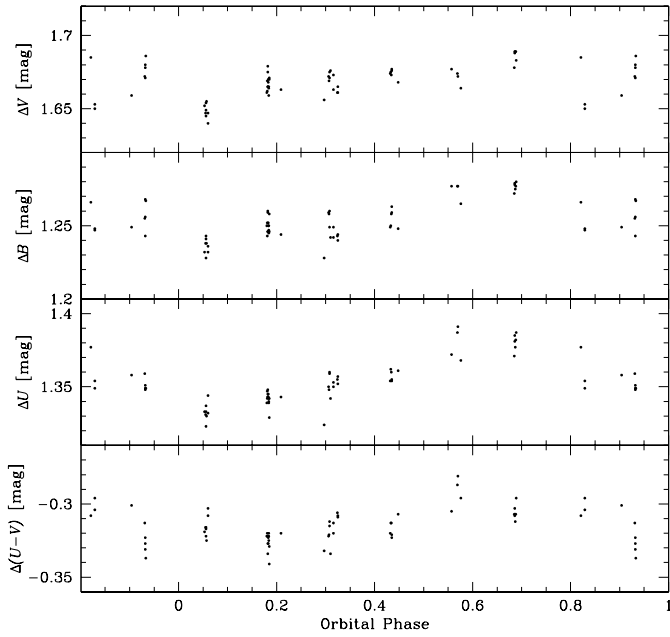


Fig. 3. Long-term light variations of WR 140 (data from Table 3)

between the lightcurves in each of the three passbands, which would be difficult to explain by variability of emission lines. The origin of the small-amplitude random continuum variations of WR 137 is possibly related to dynamical wind instabilities, resulting in temperature effects at the “pseudo-photospheric” level.

3.2. WR 140

WR 140 = HD 193793 (WC7 + O4-5) is another periodic dust maker. Williams et al. (1978, 1987a, 1987b, 1990) and Williams (1997) reported variations in the IR, revealing brightenings in 1977, 1985, and in 1993, which they attributed to the building of dust grains in the WR 140 wind with a period of 7.94 yr. The re-occurrence of the heated dust has been interpreted as due to wind-wind interaction in a binary system. Earlier spectroscopic studies failed to reveal the binary motion. However, a re-analysis of earlier published radial velocities and using the period in the IR (7.94 yr) led to a successful determination of the orbit (Williams et al. 1987c). It was found that the grain formation coincides with the periastron passage (PP) in the system (actually occurring before PP). This discovery was later confirmed by Moffat et al. (1987) and now presents the basic model for studies of WR 140. Williams et al. (1990) and van der Hucht et al. (1991) reported on variability of WR 140 at X-ray, UV, IR and radio-wavelengths. Our photometry of WR 140 is presented in Table 3 and the light curves are shown in Fig. 3. From Fig. 3, there is clear evidence for a dip in the light in 1993, between orbital phases ~ 0.9 and 1.1. The dip is seen in all passbands and should therefore be due to continuum light attenuation. The amplitude of the “eclipse” in the V passband is 0.03 mag.

Table 3. Differential photometry of WR 140 (= HD 193793) – in the sense comparison star HD 193888 minus WR 140. Orbital phases are calculated with $P = 2900$ d and $T_0 = 1985.26$.

Year	JD-2400000	orb. phase	ΔV [mag]	ΔB [mag]	ΔU [mag]
1991	48540.340	0.821	1.685	1.266	1.377
	48563.250	0.829	1.650	1.247	1.354
	48565.256	0.829	1.653	1.248	1.349
1992	48781.539	0.904	1.659	1.249	1.358
	48860.432	0.931	1.672	1.255	1.359
	48861.420	0.932	1.678	1.256	1.351
	48862.457	0.932	1.680	1.268	1.349
	48863.434	0.932	1.671	1.243	1.348
1993	48865.387	0.933	1.686	1.267	1.349
	49212.469	0.053	1.652	1.232	1.333
	49220.422	0.055	1.647	1.238	1.331
	49221.379	0.056	1.649	1.243	1.333
	49222.410	0.056	1.654	1.241	1.337
	49223.396	0.056	1.645	1.228	1.323
	49224.413	0.057	1.655	1.238	1.330
1994	49233.362	0.060	1.647	1.236	1.344
	49234.373	0.060	1.640	1.232	1.332
	49582.463	0.180	1.661	1.250	1.339
	49584.433	0.181	1.669	1.252	1.347
	49585.395	0.181	1.662	1.243	1.342
	49586.402	0.182	1.679	1.259	1.345
	49586.422	0.182	1.675	1.260	1.348
	49587.385	0.182	1.665	1.246	1.343
	49587.402	0.182	1.665	1.246	1.343
	49589.392	0.183	1.670	1.252	1.343
	49589.411	0.183	1.668	1.250	1.345
	49594.392	0.184	1.664	1.250	1.342
	49594.410	0.184	1.659	1.245	1.339
	49594.428	0.184	1.665	1.247	1.340
49595.345	0.185	1.671	1.258	1.342	
49596.352	0.185	1.670	1.246	1.329	
49666.296	0.209	1.663	1.244	1.343	
1995	49922.534	0.297	1.656	1.228	1.324
	49947.473	0.306	1.672	1.259	1.350
	49949.451	0.307	1.669	1.258	1.348
	49953.368	0.308	1.675	1.249	1.360
	49954.396	0.308	1.671	1.260	1.359
	49958.414	0.310	1.676	1.242	1.342
	49976.408	0.316	1.673	1.249	1.353
	49977.368	0.316	1.663	1.242	1.350
	49998.263	0.324	1.661	1.243	1.355
	50001.288	0.325	1.661	1.240	1.352
	50003.256	0.325	1.665	1.244	1.357
1996	50313.427	0.432	1.674	1.249	1.354
	50317.392	0.433	1.675	1.250	1.362
	50318.402	0.434	1.673	1.258	1.360
	50321.401	0.435	1.677	1.259	1.354
	50322.369	0.435	1.676	1.263	1.355
	50359.295	0.448	1.668	1.248	1.361
1997	50676.407	0.557	1.677	1.277	1.372
	50711.345	0.569	1.674	1.277	1.387
	50714.301	0.570	1.672	1.277	1.391
	50730.294	0.576	1.664	1.265	1.368
1998	51046.413	0.685	1.678	1.272	1.371
	51049.369	0.686	1.689	1.278	1.381
	51050.356	0.686	1.688	1.279	1.385
	51053.389	0.687	1.689	1.275	1.377
	51054.365	0.688	1.689	1.277	1.382
	51059.329	0.689	1.683	1.280	1.387

Table 4. Differential photometry of WR 148 (= HD 197406) – in the sense comparison star HD 197619 minus WR 148. Orbital phases are calculated with $P = 4.317364$ d and $T_0 = \text{JD } 2432434.4$ (Drissen et al. 1986).

Year	JD-2400000	orb. phase	ΔV [mag]	ΔB [mag]	ΔU [mag]
1993	49212.502	0.19	-1.908	-2.313	-2.231
	49220.454	0.03	-1.929	-2.331	-2.264
	49221.402	0.25	-1.900	-2.287	-2.209
	49222.432	0.49	-1.910	-2.302	-2.215
	49223.419	0.72	-1.896	-2.288	-2.213
	49224.434	0.95	-1.941	-2.334	-2.257
	49233.384	0.03	-1.913	-2.309	-2.234
	49234.395	0.26	-1.866	-2.253	-2.170
	49235.373	0.49	-1.878	-2.288	-2.215
1994	49582.507	0.89	-1.987	-2.382	-2.307
	49584.468	0.35	-1.951	-2.344	-2.263
	49585.424	0.57	-1.884	-2.222	-2.134
	49586.454	0.81	-1.923	-2.326	-2.248
	49587.429	0.03	-1.955	-2.348	-2.270
	49589.442	0.50	-1.951	-2.343	-2.271
	49594.476	0.67	-1.928	-2.329	-2.251
	49595.373	0.87	-1.973	-2.360	-2.281
	49596.375	0.10	-1.962	-2.353	-2.272
1996	50313.505	0.21	-1.942	-2.337	-2.263
	50317.435	0.12	-1.955	-2.365	-2.284
	50318.436	0.35	-1.964	-2.346	-2.266
	50321.462	0.05	-1.947	-2.321	-2.247
	50322.404	0.27	-1.922	-2.307	-2.222
	50358.324	0.59	-1.899	-2.292	-2.209
1997	50676.447	0.27	-1.922	-2.284	-2.201
	50714.327	0.05	-1.913	-2.281	-2.212
	50730.322	0.75	-1.876	-2.250	-2.175
	50731.317	0.98	-1.905	-2.272	-2.199
	50732.292	0.21	-1.883	-2.249	-2.170
1998	51046.452	0.98	-1.942	-2.316	-2.245
	51049.406	0.66	-1.933	-2.303	-2.229
	51050.390	0.89	-1.930	-2.302	-2.207
	51050.405	0.89	-1.924	-2.304	-2.212
	51053.419	0.59	-1.930	-2.299	-2.220
	51054.392	0.81	-1.924	-2.288	-2.218
	51058.419	0.75	-1.936	-2.303	-2.226
	51059.399	0.97	-1.949	-2.321	-2.245

Two remarkable features are to be mentioned. First, the very broad shape of the light minimum, assuming a smooth trend between yearly data. After 1993, the light gradually increased to reach the “pre-eclipse” level in 1997, or even 1998. Considering the “eclipse” to be caused by an obscuration of the star(s) by the wind, the light curves strongly suggest that a dust envelope was built up around the WR star by the wind-wind interaction at the PP, which was gradually dispersed in the following years. Possibly it is the same dust observed in the IR when still heated. Second, it is apparent (Fig. 3) that the amplitude of the eclipse increases towards shorter wavelengths. In the lower panel of Fig. 3, the variation of the colour $\Delta(U - V)$ is shown, which is in the sense: WR 140 colour gets redder when its light is attenuated. This conclusion is easily obtained when considering the magnitudes of the comparison star HD 193888, which are: $V = 8.54$, $B - V = -0.07$, $U - B = -0.25$, and $U - V = -0.32$. The amplitude of the colour variation in $U - V$ of WR 140 is 0.04 mag (again Fig. 3). As is well known, the

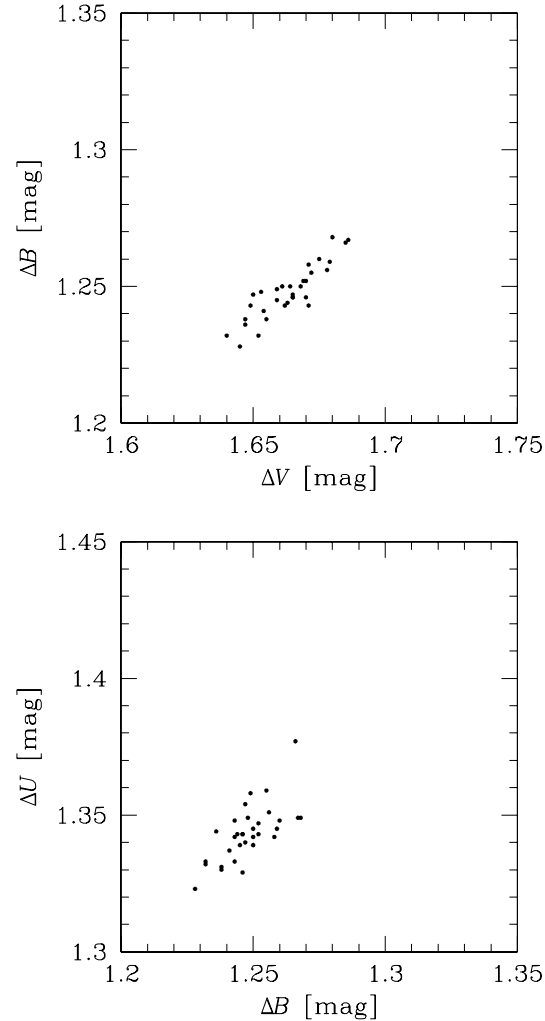


Fig. 4. WR 140. Random light variability correlations for 1994 (data from Table 3)

main source of opacity, (non-relativistic) electron scattering, has no effect on colours. Thus, in this case electron scattering alone is not sufficient, and an additional opacity source should be introduced, possibly Rayleigh (or Mie) scattering by small carbon dust particles.

Occasional “eclipses” have been observed in the carbon-rich late-type WC stars WR 103, WR 113, and WR 121 (for a history of “eclipses” see Veen et al. 1998). In these cases the “eclipses” were caused by occasional formation of dust in the line-of-sight. Although dust formation in the winds of late-type WC stars is now well established, the problem with grain condensation in the very hostile environments where the grains are believed to form remains unsolved. Clearly, a trigger is needed to start the grain formation. In the case of WR 140, this could be the shock compression in the colliding winds at PP. We assume that the fading of WR 140 shortly after PP is due to dust condensation in the wind of the WC star. After the condensation ceases the star brightens again because the dust is blown away and gradually dispersed. The “eclipses” studied by Veen et al. (1998) have typical amplitudes of several tenths of a magnitude and

last from several days up to a month. In contrast, the amplitude of the light dip in WR 140 is much smaller and the recovery of brightness lasts several years. This implies continuing supply (expanding from the PP production + new?) of dust, even 2 – 3 years after PP. If there is new dust, this would be really surprising, since the trigger seems no longer to be effective. Following the procedure of Veen et al. (1998, using their Eqs. (5), (6), and (7)) and taking the terminal velocity $v_\infty = 2900 \text{ km s}^{-1}$ from Eenens & Williams (1994), we obtain for the distance R_{cc} of the dust formation region from the WC star in WR 140: $R_{cc} \sim 300\,000 R_\odot$. This is only a rough estimate, but it is much larger than the respective distances for all “eclipses” studied by Veen and co-workers. It is also much larger than the radius of the shell of WR 140 obtained by Williams et al. (1987a) which is $R_{shell} = 1490 R_\odot$. Taking for the carbon particle density 1.85 g cm^{-3} we get for the dust mass production rate (over unit area) the value $\dot{M}_d = 2 \cdot 10^{-13} \text{ kg m}^{-2} \text{ s}^{-1}$. These results should be taken with caution because of the small amplitude of the “eclipse” in WR 140 and of possible deviations from the model used (e.g. continued supply of dust after PP).

WR 140 was observed photometrically during PP in 1977 by Fernie (1978) but no changes of brightness were found. This is likely due to his low precision data.

Like WR 137, the observations of WR 140 also show small-amplitude, day-to-day random light variations (amplitudes up to 0.02 mag), in addition to the eclipse variation. Fig. 4 shows the correlations of the random light variations in UBV , indicating that they are likely due to continuum rather than emission line variations (similar to WR 137, Fig. 2). Dynamical wind instabilities could be the origin, as in WR 137. Moffat & Shara (1986) suggested a 6.25 d period for the light variations they observed in WR 140, which, however, does not fit our data. Our observations during 1991 - 1998 cover 90% of the orbit. It remains to be seen whether the forthcoming PP in 2001 will repeat the light curve so far observed.

3.3. WR 148

WR 148 (= HD 197406, WN8 + c?) is a single-line spectroscopic binary, possibly hosting a compact companion. The star has been studied by Bracher (1979). She determined the orbital period as $P = 4.3174 \text{ d}$ and also found light variations with the same period and an amplitude of 0.04 mag in V . Further spectroscopic studies by Moffat & Seggewiss (1979, 1980) revealed an unusually low mass function of the system, which was later confirmed by Drissen et al. (1986): $f(m) = 0.28 M_\odot$. WR 148 has also an exceptionally large distance from the galactic plane, $z = 500 - 800 \text{ pc}$ (Moffat & Isserstedt 1980; Dubner et al. 1990). Smith et al. (1996) found that WR 148 is a WN8 star. The low mass function and high z value led Moffat & Seggewiss (1980) to advance the idea that WR 148 harbours a compact companion as product of a supernovae explosion some 5 Myr ago. In their model, the companion is orbiting within the WR envelope. As the companion orbits around the WR star the projected envelope density varies. This is the origin of the light variations of WR 148, because electron scattering occurs in this

envelope. Photometric studies by Antokhin (1984), Moffat & Shara (1986), and Marchenko et al. (1996) confirmed the light variations found by Bracher (1979) with an amplitude of 0.03 mag in V and also point to the very “noisy” appearance of the light curve. (With the ephemeris of Drissen et al. (1986), the light minimum occurs at phase zero with the WR star in front). Marchenko et al. (1996) noted the unusual wide-shaped light minimum, quite different from other known WR + O systems with atmospheric eclipses and a V-shaped light minimum (Lamontagne et al. 1996). For WR 148, Marchenko et al. suggested that the secondary light arises from an extended hot cavity in the WR envelope, near the companion, and which is ionized by X-rays. According to Marchenko et al., the rather weak X-ray source observed in WR 148 (Pollock et al. 1995) may be explained by the hot X-ray cavity being locally embedded in the WR envelope. Presently, the evolutionary status of WR 148 remains unclear and the companion could be either a B2-B4 III-V star or a relativistic object (as deduced from the mass function, Marchenko et al. 1996).

Our photometry is presented in Table 4 and the light curves are shown in Fig. 5, plotted with the ephemeris of Drissen et al. (1986). From Fig. 5 it is apparent that our light curves in 1993 are similar to the light curves published by Moffat & Shara (1986). The minimum occurs at phase zero. The 1994 light curves, however, show a remarkable change in their shape and mean light level. Random light variations, already noted in other works, could well contribute to the disturbance of the light curve shape, but it is unlikely that they would change the mean light. Furthermore, long-term changes in mean light appear to be correlated in U , B , and V (Fig. 5). Therefore, they too should be due to changes in continuum light.

There is a strong evidence for a long-term variation of the mean light. Although the time-base is too short, there are some indications that the long-term variation is periodic, possibly with a cycle of about 4 years. Marchenko et al. (1998b) point to a possible “overall brightening” of WR 148 in 1994 and 1995. As shown in Fig. 5, it is obvious that in 1993 the mean light was even some 0.05 mag higher, as in 1994. This long-term variation completely masks the short-term binary variations if the whole data set is depicted in one plot. Therefore we plotted the data separately for each year in Fig. 5.

Taking into account the model of Marchenko et al. (1996), the long-term light variations in WR 148 could be due to variations of the size of the hot X-ray cavity. Further conclusions at that time seem premature. A comment should be given on the observation at JD 2449585.4, phase = 0.57 (the companion \sim in front), which strongly deviates from the regular light curve of 1994. As we can exclude observational errors as a reason for this measurement, it has to have some astrophysical origin. For instance, an event of accretion onto a compact companion could be invoked to explain this flare-like burst.

Flickering and flaring of WR 148 on different time-scales have been reported by Antokhin & Cherepashchuck (1989), Zhilyaev et al. (1995) and Khalack & Zhilyaev (1995). Matthews et al. (1992) looked for flares in the WR star EZ Canis Majoris (WR 6 = HD 50896, WN5) and reported one flare event.

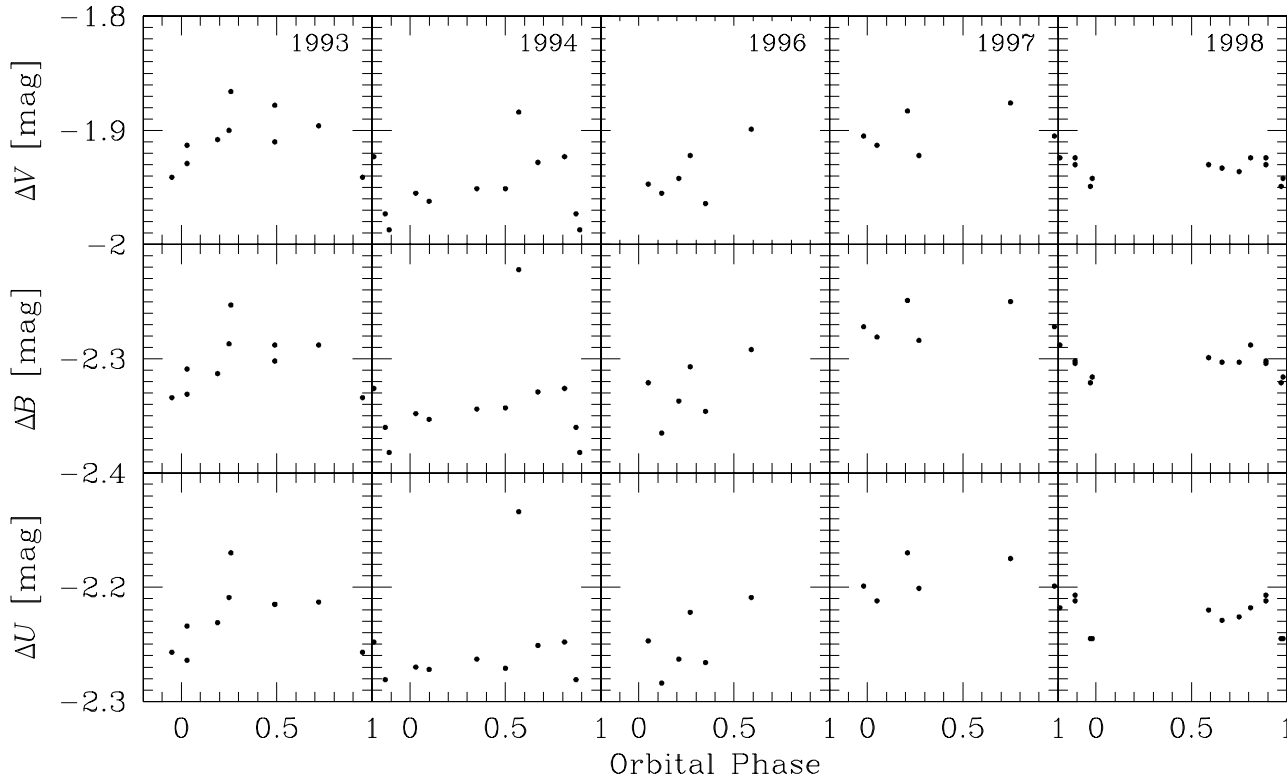


Fig. 5. Light curves of WR 148 (data from Table 4)

Flare-type activity of EZ CMa was also observed by Duijsens et al. (1996). This star is in many respects similar to WR 148, e.g. showing light variations with a 3.77 d period, long-term changes in the light curve, and a possible WR + c binary status (Firmani et al. 1980; Balona et al. 1989; Duijsens et al. 1996).

3.4. WR 153

WR 153 (= HD 211853 = GP Cep) is a quadruple system (Massey 1981) with orbital periods 6.6884 d (pair A, WR + O) and 3.4696 d (pair B, WR + O or O + O). Earlier spectroscopic studies by Hiltner (1945) and Bracher (1968) revealed radial velocity variations due to binary motion with a period of 6.68 d. Panov & Seggewiss (1990) reanalysed Hiltner's velocity data and found evidence for two WR stars, one in each pair. WR 153 has been observed photometrically by Hjellming & Hiltner (1963), Stepien (1970), Moffat & Shara (1986), Panov & Seggewiss (1990), and Annuk (1994), all detecting eclipses with both periods, 6.6884 d and 3.47 d. Finally, Annuk (1994) refined the second period to 3.4696 d, in agreement with the velocity data of Massey (1981). However, in the recent analysis of WR star light curves by Lamontagne et al. (1996) the 3.47 d variation of pair B could not unambiguously be extracted from their data.

Our photometry of WR 153 is presented in Table 5 and the light curves are shown in Fig. 6a and b, with the 6.6884 d and 3.4696 d periods, respectively. From Fig. 6, our data are consistent with the ephemeris of Massey (1981) and Annuk (1994), respectively. Since the true shape of both light curves is unknown,

no allowance is made for the 3.47 d period in Fig. 6a, where it is superimposed on the 6.69 d light variations. In Fig. 6b, the data points around the 6.69 d period minimum (at phases from 0.96 to 0.13 in Fig. 6a) have been removed.

The light curve with the 6.69 d period (pair A) is probably due to an atmospheric eclipse (only one, V-shaped light minimum!). In pair B, two light minima are seen due to a core eclipse in that pair. Independent evidence can be obtained from the HIPPARCOS photometry data. We made a period search, using 122 data-points from HIPPARCOS. The analysis was performed with the PERIBM procedure, developed at the Astronomical Institute of the University of Vienna (latest version from: <ftp://dsn.astro.univie.ac.at/pub/PERIOD98/current/>). Our analysis clearly shows that there are peaks at $f1 = 0.5763641 \text{ d}^{-1}$, corresponding to a 1.735 d period, and at $f2 = 0.1495867 \text{ d}^{-1}$, corresponding to the 6.69 d period. The 1.735 d period is exactly 1/2 of the 3.47 d period and the reason that it shows up in the amplitude spectrum is because of the double-wave light curve (two eclipses in pair B), consistent with our ground-based photometry. Moffat & Shara (1986) also deduced that pair A had a single minimum at phase 0.00 ($P = 6.69 \text{ d}$) and pair B had a double minimum at phases 0.00 and 0.50 ($P = 3.47 \text{ d}$).

4. Conclusions

Our photometry of WR 137 reveals only small amplitude ($\leq 0.03 \text{ mag}$ in the V passband) random light variations. No periodicity could be found. These variations should be attributed

Table 5. Photometry of WR 153 (= HD 211853). The comparison star is HD 211430 with $V = 7.465$, $B - V = -0.054$, and $U - B = -0.490$. Orbital phases “1” are calculated with $P1 = 6.6884$ d and $T_0 = \text{JD } 2443690.32$ (Massey 1981), orbital phases “2” with $P2 = 3.4696$ d and $T_0 = \text{JD } 2443689.16$ (Annuk 1994)

Year	JD-2400000	Orb. Phase		V [mag]	B [mag]	U [mag]	$B - V$ [mag]	$U - B$ [mag]
		“1”	“2”					
1991	48448.527	0.41	0.73	8.979	9.352	8.749	0.373	-0.603
	48510.472	0.67	0.59	9.001	9.373	8.765	0.372	-0.608
	48510.487	0.68	0.59	8.996	9.368	8.766	0.372	-0.602
	48510.504	0.68	0.60	8.995	9.372	8.769	0.377	-0.603
	48510.518	0.68	0.60	8.992	9.370	8.774	0.378	-0.596
	48511.524	0.83	0.89	8.992	9.372	8.771	0.380	-0.601
	48511.538	0.83	0.89	8.995	9.375	8.775	0.380	-0.600
	48511.551	0.83	0.90	8.995	9.372	8.777	0.377	-0.595
	48511.567	0.84	0.90	8.994	9.377	8.775	0.383	-0.602
	48511.580	0.84	0.91	8.996	9.379	8.784	0.383	-0.595
	48511.591	0.84	0.91	9.000	9.380	8.788	0.380	-0.592
	48512.519	0.98	0.18	9.042	9.428	8.818	0.386	-0.610
	48513.479	0.12	0.45	9.052	9.445	8.855	0.393	-0.590
	48514.502	0.28	0.75	8.978	9.353	8.737	0.375	-0.616
	48538.446	0.86	0.65	8.972	9.363	8.752	0.391	-0.611
	48539.464	0.01	0.94	9.068	9.462	8.862	0.394	-0.600
	1993	49220.514	0.83	0.23	8.979	9.367	8.751	0.388
49221.490		0.98	0.52	9.086	9.478	8.875	0.392	-0.603
49222.523		0.13	0.81	8.972	9.363	8.743	0.391	-0.620
49223.488		0.28	0.09	8.991	9.380	8.768	0.389	-0.612
49224.519		0.43	0.39	8.972	9.361	8.750	0.389	-0.611
49233.431		0.76	0.96	9.028	9.421	8.805	0.393	-0.616
49233.446		0.77	0.96	9.929	9.418	8.808	0.389	-0.610
49234.449		0.92	0.25	8.990	9.383	8.766	0.393	-0.617
49234.462		0.92	0.25	8.986	9.382	8.761	0.396	-0.621
49234.474		0.92	0.25	8.992	9.379	8.760	0.387	-0.619
49234.490		0.92	0.26	8.994	9.382	8.764	0.388	-0.618
49234.503		0.93	0.26	8.994	9.380	8.760	0.386	-0.620
49234.517		0.93	0.27	8.989	9.382	8.764	0.393	-0.618
49235.416		0.06	0.53	9.072	9.470	8.858	0.398	-0.612
49235.429		0.06	0.53	9.076	9.478	8.862	0.402	-0.616
49235.441		0.07	0.54	9.085	9.483	8.858	0.398	-0.625
1994		49582.539	0.96	0.58	9.040	9.431	8.835	0.391
	49584.494	0.25	0.14	8.993	9.381	8.770	0.388	-0.611
	49585.476	0.40	0.42	8.994	9.380	8.771	0.386	-0.609
	49586.502	0.55	0.72	8.976	9.368	8.763	0.392	-0.605
	49587.477	0.70	0.00	9.009	9.393	8.787	0.384	-0.606
	49589.498	0.00	0.58	9.051	9.448	8.844	0.397	-0.604
	49594.505	0.75	0.02	9.022	9.418	8.817	0.396	-0.601
	49595.417	0.89	0.29	8.985	9.375	8.763	0.390	-0.612
	49596.402	0.03	0.57	9.069	9.464	8.845	0.395	-0.619
	49666.396	0.50	0.74	8.984	9.379	8.767	0.395	-0.612
	1995	49975.516	0.72	0.84	9.002	9.391	8.781	0.389
49977.524		0.02	0.42	9.054	9.436	8.832	0.382	-0.604

to the continuum and they are probably due to dynamical wind instabilities.

WR 140 exhibited remarkable light variations and a shallow light dip is seen in all passbands shortly after periastron passage in 1993. The light attenuation lasted until 1997 or even 1998, probably because of a dust envelope built around the WR star by wind-wind interaction at periastron passage. The dust envelope was gradually dispersed. From the wavelength dependence of the light attenuation, we find strong evidence for Rayleigh (Mie-like) scattering, contributing to the opacity, in addition to electron scattering.

For WR 148, our photometric study confirms the 4.317364 d light variation, but reveals occasional scatter, disturbing the light curve shape. On one occasion, we see a flare-like event at a phase

when the companion is in front. Our photometry reveals long-term variations of the mean light and, possibly, of the amplitude of the regular variation. There is some evidence for a periodicity of the long-term light variation and a 4 year cycle cannot be ruled out.

Our photometry of WR 153 is consistent with the quadruple model for this star and both the 6.6884 d and the 3.4696 d periods are seen in the light. In pair A (6.6884 d period) we found evidence for an atmospheric eclipse, in agreement with the results of other works, while in pair B (3.4696 d period) the eclipse is probably photospheric (core eclipse).

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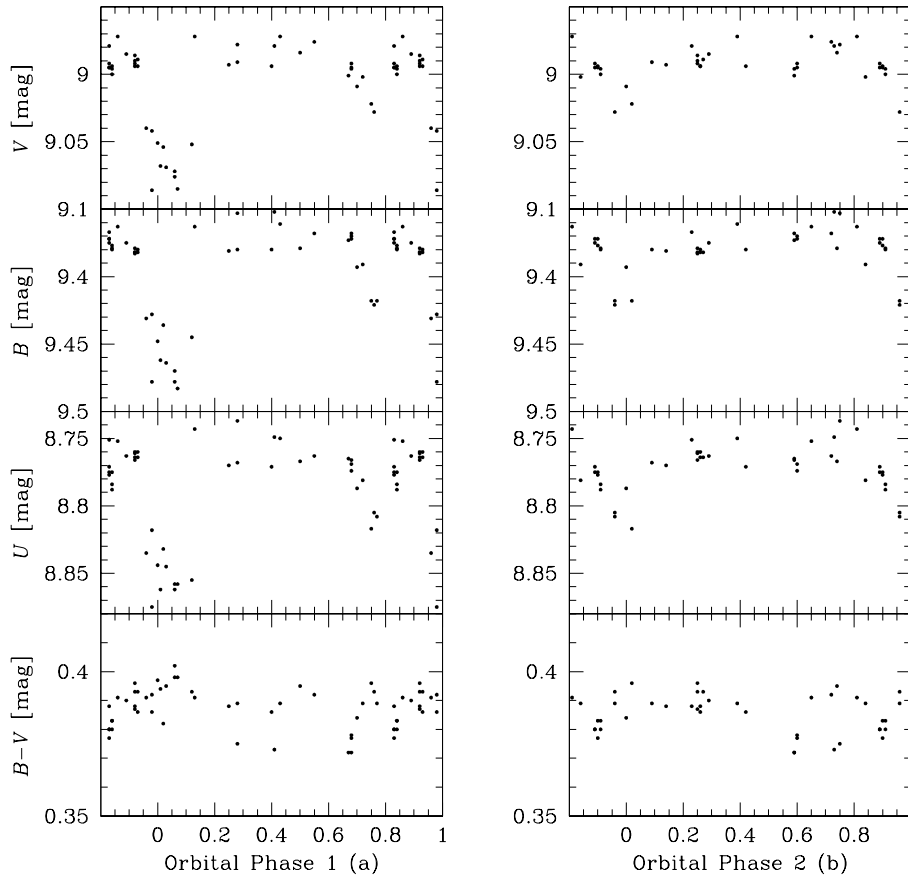


Fig. 6. Light curves of WR 153 with **a** $P1 = 6.6884$ d and **b** $P2 = 3.4696$ d (data from Table 5)

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