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# 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 independant 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 $10^{-4}$ $M_\odot$ 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 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.

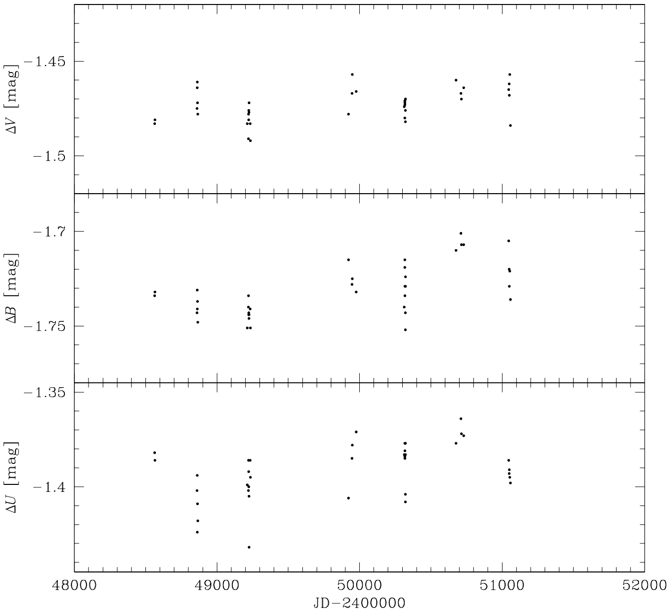

**Fig. 1.** Light curves of WR 137 (data from Table 2)

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.

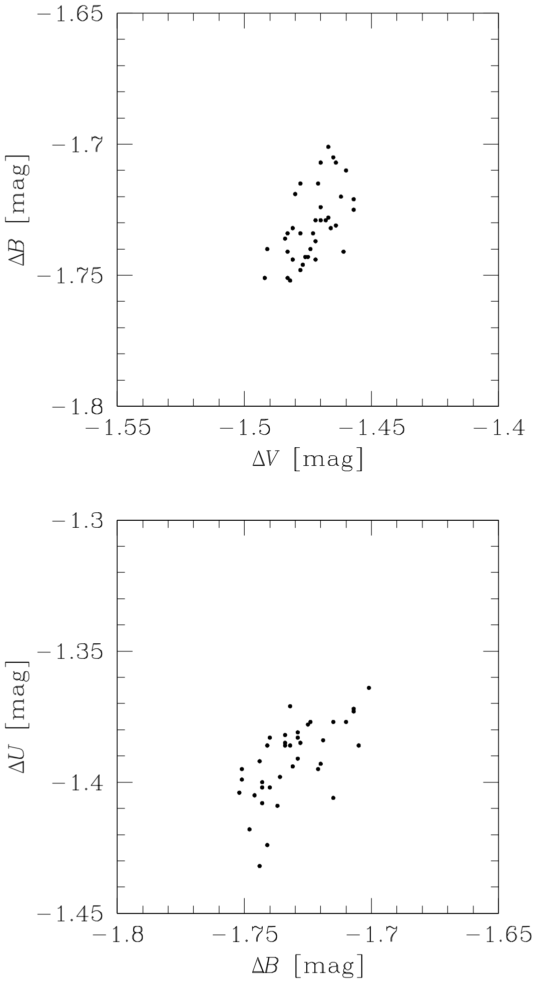

**Fig. 2.** Random light variability correlations for WR 137 (data from Table 2)

## 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 Annuk (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 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.

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

| Year | JD-2400000 | $\Delta V$ [mag] | $\Delta B$ [mag] | $\Delta U$ [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 |

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 $B$)

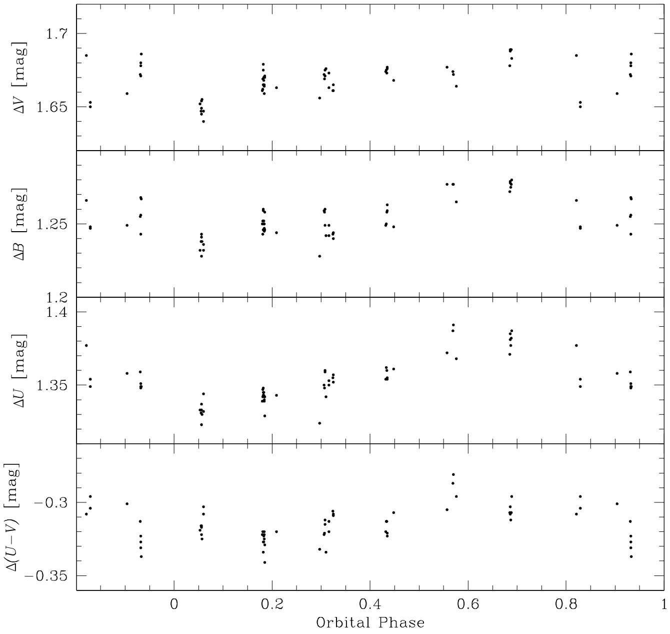

**Fig. 3.** Long-term light variations of WR 140 (data from Table 3)

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 | $\Delta V$ [mag] | $\Delta B$ [mag] | $\Delta U$ [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 |
| | 48865.387 | 0.933 | 1.686 | 1.267 | 1.349 |
| 1993 | 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 |
| | 49233.362 | 0.060 | 1.647 | 1.236 | 1.344 |
| | 49234.373 | 0.060 | 1.640 | 1.232 | 1.332 |
| 1994 | 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 $T_0 =$ JD 2432434.4 (Drissen et al. 1986).

| Year | JD-2400000 | orb. phase | $\Delta V$ [mag] | $\Delta B$ [mag] | $\Delta U$ [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 |

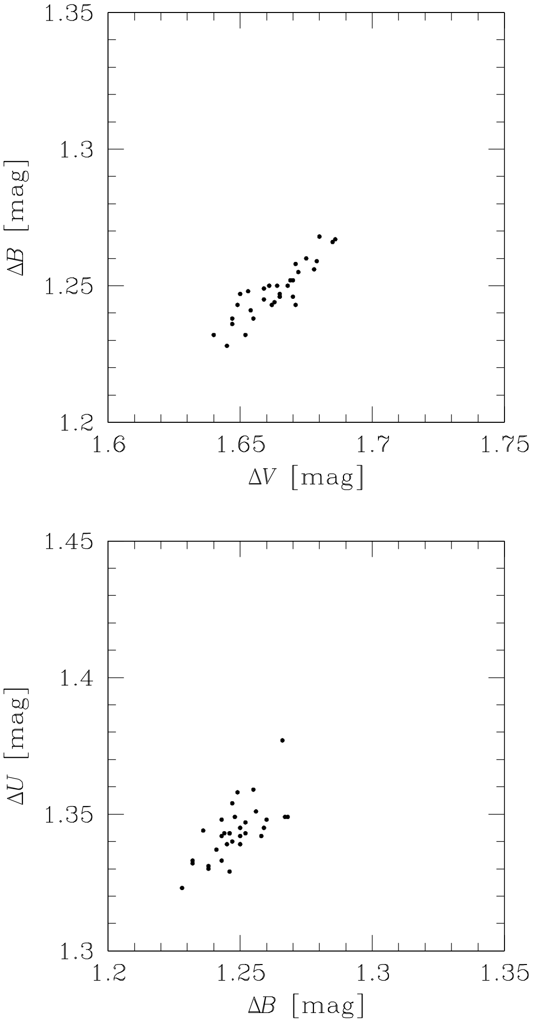

**Fig. 4.** WR 140. Random light variability correlations for 1994 (data from Table 3)

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 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 $v_\infty = 2900\,\mathrm{km\,s^{-1}}$ from Eenens & Williams (1994), we obtain for the distance $R_{\rm cc}$ of the dust formation region from the WC star in WR 140: $R_{\rm cc} \sim 300\,000\,R_\odot$. 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 $1.85\,\mathrm{g\,cm^{-3}}$ we get for the dust mass production rate (over unit area) the value $\dot{M}_d = 2\,10^{-13}\,\mathrm{kg\,m^{-2}\,s^{-1}}$. 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 $P = 4.3174$ 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, $z = 500 - 800$ 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" appearence 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.

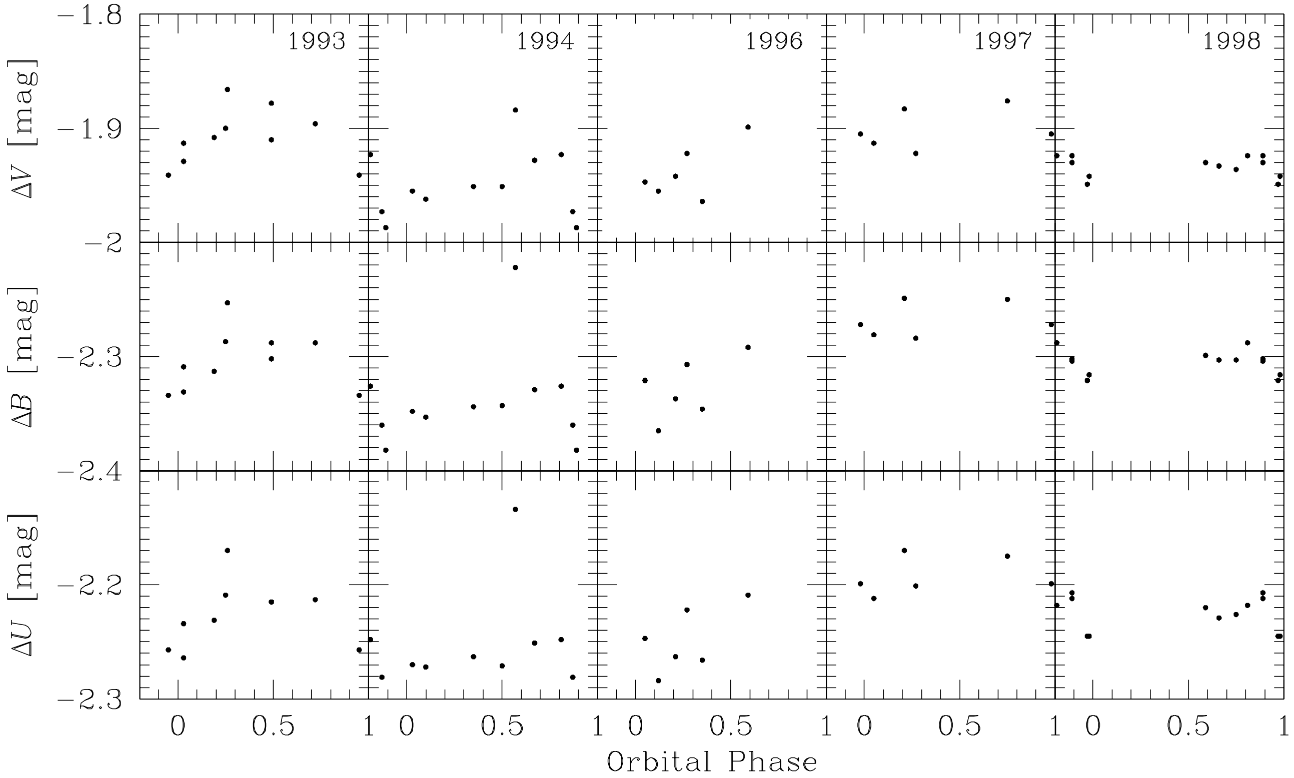

**Fig. 5.** Light curves of WR 148 (data from Table 4

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 $f1 = 0.5763641$ d$^{-1}$, corresponding to a 1.735 d period, and at $f2 = 0.1495867$ 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 ($P = 6.69$ d) and pair B had a double minimum at phases 0.00 and 0.50 ($P = 3.47$ d).

## 4. Conclusions

Our photometry of WR 137 reveals only small amplitude ($\leq$ 0.03 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 $T_0 =$ JD 2443690.32 (Massey 1981), orbital phases "2" with $P2 = 3.4696$ d and $T_0 =$ JD 2443689.16 (Annuk 1994)

| Year | JD-2400000 | Orb. Phase |  | $V$ | $B$ | $U$ | $B-V$ | $U-B$ |
|---|---|---|---|---|---|---|---|---|
|  |  | "1" | "2" | [mag] | [mag] | [mag] | [mag] | [mag] |
| 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 | −0.616 |
|  | 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 | −0.596 |
|  | 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 | -0.610 |
|  | 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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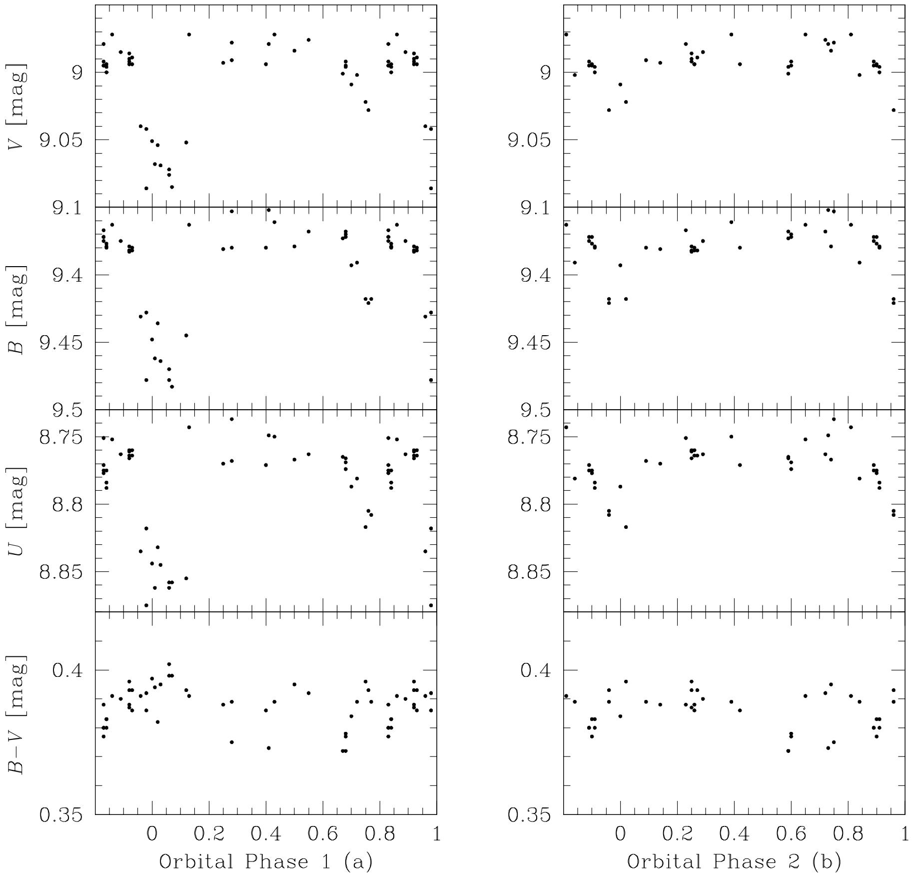

**Fig. 6.** Light curves of WR 153 with **a** $P1 = 6.6884$ d and **b** $P2 = 3.4696$ d (data from Table 5)

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## References

Antokhin I.I., 1984, Astron. Tsirk. 1350, 1
Antokhin I.I., Cherepashchuck A.M., 1989, Sov. Astron. Lett. 15(4), 303
Antokhin I.I., Bertrand J.F., Lamontagne R., et al., 1995, AJ 109, 817
Annuk K., 1994, A&A 282, 137
Annuk K., 1995, In: van der Hucht K.A., Williams P.M. (eds.) Wolf-Rayet Stars: Binaries, Colliding Winds, Evolution, IAU Symposium 163, Kluwer Acad. Publ., Dordrecht, p. 231
Balona L.A., Egan J., Marang F., 1989, MNRAS 240, 103
Bracher K., 1968, PASP 80, 165
Bracher K., 1979, PASP 91, 827
Drissen L., Lamontagne R., Moffat A.F.J., et al., 1986, ApJ 304, 188
Dubner G.M., Niemela V.S., Purton C.R., 1990, AJ 99, 857
Duijsens M.F.J., van der Hucht K.A., van Genderen A.M., et al., 1996, A&AS 119, 37
Eenens P.R.J., Williams P.M., 1994, MNRAS 269, 1082
Fernie J.D., 1978, Inf. Bull. Variable Stars No. 1377
Firmani C., Koenigsberger G., Bisiacchi G.F., et al., 1980, ApJ 239, 607
Gosset E., Vreux J.-M., Manfroid J., et al., 1990, A&AS 84, 377
Hiltner W.A., 1945, ApJ 101, 356
Hjellming R.M., Hiltner W.A., 1963, ApJ 137, 1080
Khalack V.R., Zhilyaev B.E., 1995, Kinemat. Phys. Celest. Bodies 13 (2)
Lafler J., Kinman T.D., 1965, ApJS 11, 216
Lamontagne R., Moffat A.F.J., 1987, AJ 94, 1008
Lamontagne R., Moffat A.F.J., Drissen L., et al., 1996, AJ 112, 2227
Maeder A., 1985, A&A 147, 300
Maeder A., 1996, In: Vreux J.M., Detal A., Fraipont-Caro D., Gosset E., Rauw G. (eds.) Wolf-Rayet Stars in the Framework of Stellar Evolution, 33rd Liège Internat. Astrophys. Coll., Liège, Université de Liège, p. 39
Marchenko S.V., Pikhun A.I., 1992, Kinemat. Phys. Celest. Bodies 8, 24
Marchenko S.V., Moffat A.F.J., Lamontagne R., et al., 1996, ApJ 461, 386
Marchenko S.V., Moffat A.F.J., van der Hucht K.A., et al., 1998a, A&A 331, 1022
Marchenko S.V., Moffat A.F.J., Eversberg T., et al., 1998b, MNRAS 294, 642
Marchenko S.V., Moffat A.F.J., Grosdidier Y., 1999, ApJ 522, 433
Massey P., 1981, ApJ 244, 157
Matthews J.M., Moffat A.F.J., 1994, A&A 283, 493
Matthews J.M., Moffat A.F.J., Marchenko S.V., 1992, A&A 266, 409
Moffat A.F.J., Isserstedt J., 1980, A&A 85, 201
Moffat A.F.J., Seggewiss W., 1979, A&A 77, 128
Moffat A.F.J., Seggewiss W., 1980, A&A 86, 87
Moffat A.F.J., Shara M.M., 1986, AJ 92, 952

Moffat A.F.J., Lamontagne R., Williams P.M., et al., 1987, ApJ 312, 807

Moffat A.F.J., Drissen L., Lamontagne R., et al., 1988, ApJ 334, 1038

Moffat A.F.J., Lépine S., Henriksen R.N., et al., 1994, Ap&SS 216, 55

Panov K.P., Seggewiss W., 1990, A&A 227, 117

Panov K.P., Pamukchiev I.Ch., Christov P.P., et al., 1982, C. R. Acad. Bulg. Sci. 36, 717

Pollock A.M.T., Haberl F., Corcoran M.F., 1995, In: van der Hucht K.A., Williams P.M. (eds.), Wolf-Rayet Stars: Binaries, Colliding Winds, Evolution, IAU Symposium 163, Kluwer Acad. Publ., Dordrecht, p. 512

Pyper D.M., 1966, ApJ 144, 13

Rauw G., Gosset E., Manfroid, J., et al., 1996, A&A 306, 783

Robert C., 1994, Ap&SS 221, 137

Robert C., Moffat A.F.J., Bastien P., et al., 1989, ApJ 347, 1034

Smith L.F., Shara M.M., Moffat A.F.J., 1996, MNRAS 281, 163

Stepien K., 1970, Acta Astron. 20, 117

Underhill A.B., 1992, ApJ 398, 636

van der Hucht K.A., Williams P.M., Pollock A.M.T., et al., 1991, In: van der Hucht K.A., Hidayat B.(eds.) Wolf-Rayet Stars and Interrelations with other Massive Stars in Galaxies, IAU Symposium 143, Kluwer Acad. Publ., Dordrecht, p. 251

van Genderen A.M., van der Hucht K.A., Steemers W.J.G., 1987, A&A 185, 131

Veen P.M., van Genderen A.M., van der Hucht K.A., et al., 1998, A&A 329, 199

Vreux J.-M., 1985, PASP 97, 274

Williams P.M., 1997, Ap&SS 251, 321

Williams P.M., Beattie D.H., Lee T.J., et al., 1978, MNRAS 185, 467

Williams P.M., van der Hucht K.A., The P.S., 1987a, A&A 182, 91

Williams P.M., van der Hucht K.A., The P.S., 1987b, QJRAS 28, 248

Williams P.M., van der Hucht K.A., Pollock A.M.T., et al., 1990, MNRAS 243, 662

Williams P.M., van der Hucht K.A., van der Woerd H., et al., 1987c, In: Lamers H.J.G.L.M., de Loore C.W.H. (eds.) Instabilities in Luminous Early Type Stars, Reidel, Dordrecht, p. 221

Zhilyaev B.E., Khalack V.R., Verlyuk I.A., 1995, In: van der Hucht K.A., Williams P.M. (eds.) Wolf-Rayet Stars: Binaries, Colliding Winds, Evolution, IAU Symposium 163, Kluwer Acad. Publ., Dordrecht, p. 550