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Strömgren photometry of the variable Wolf-Rayet star HD 86161 = WR 16 [★]

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Summary. Strömgren uvby photometry of the Wolf-Rayet star WR 16 (HD 86161, WN 8) made in 1985/1986 is presented and discussed. The star appears to change its brightness ($\Delta m \sim 0^m06$) with a non-stable periodicity. During the time interval of our data the best quasi-period is $P = 9^d280$.

The light variations are largely due to continuum variations, while emission line variations play a minor role. Several possible explanations are offered.

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

1. Introduction

WR 16 = HD 86161 is a WN 8 type star of which the photometric variability was studied by Moffat and Niemela (1982), Manfroid et al. (1987), van Genderen et al. (1987), Lamontagne and Moffat (1987), Gosset et al. (1989), and Balona et al. (1989). From these references it can be concluded that the interpretation of the variability is a great problem with contradictory results on the periodicity.

We present and discuss in the present paper Strömgren uvby photometry made in 1985/1986, of which a preliminary report has been given by Gosset et al. (1989).

2. Observations and reductions

The observations were obtained with the 50-cm Danish Telescope at the ESO, La Silla, Chile, from 13 December 1985 through 13 January 1986 (hereafter called epoch I), from 15 February through 30 March 1986 (epoch II) and from 31 May through 8 June 1986 (epoch III). The observers who participated in Sterken's Working Group "Long-term Photometry of Variables" are listed in Table 1.

Details on the reduction procedure are given by Manfroid and Heck (1983, 1984) and the filter systems by Manfroid and Sterken (1987). Our observations were done with the Strömgren filter system no. 4.

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[★] Observations collected at the ESO, La Silla, Chile

Table 1. List of observers of the Strömgren photometry

J.D.-2440000	Observer
6412–6443	F.-J. Zickgraf
6476–6498	M. Burger
6498–6519	A. Jorissen
6581–6589	H. Steenman

During the three epochs mentioned above, WR 16 was observed once, often twice per night with two comparison stars c1 (HD 86000, B8/9 IV) and c2 (HD 85810, B8 IV/V), see Table 2, in the following sequence: c1-WR-c2-WR-c1-WR-c2-sky. The averages c1-c2 were applied to transform all c2 measurements into c1 measurements. Then for each sequence an average value for WR-c1 could be computed. The individual observations will be published elsewhere by Manfroid et al. (1989, in preparation).

The magnitude and colour differences WR 16-c1 are shown in Figs. 1 and 2 as a function of Julian Date. The typical errors in the relative values are $\pm 0^m003$. Table 2 lists the average Strömgren photometric parameters of WR 16 and the two comparison stars for the three epochs separately and their standard deviations σ . Obviously the comparison stars are stable, in contrast with WR 16.

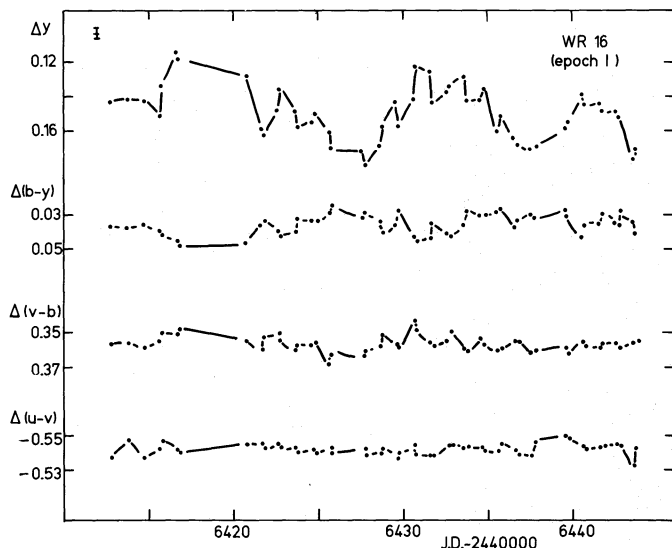
Since the colour indices m_1 , and c_1 , are of little use for stars with emission lines like WR 16, we only discuss, apart from the brightness, y , b , v , and u , also the colour indices $b-y$, $v-b$ and $u-v$.

3. The light and colour curves

Figures 1 and 2 show the light and colour curves of WR 16 relative to c1 for epoch I and epochs II, III, respectively. There is not much difference between the average brightness level and that of the colours for epoch I and II (see also Table 2). However, in epoch III, two months later, there is a clear difference: on the average the star turned out to be brighter in y by $\sim 0^m04$, redder in $b-y$ and $u-v$ by $\sim 0^m02$ and $\sim 0^m11$, respectively, and bluer in $v-b$ by $\sim 0^m02$. Consequently, the changes in the band-passes b , v and u are $\sim 0^m02$, $\sim 0^m04$ brighter and $\sim 0^m07$ fainter, respectively. A

Table 2. Average photometric Strömgen parameters of WR 16 and the comparison stars. The errors are standard deviations

Star	Epoch J.D.-2440000	y	b	v	u	$b-y$	m_1	c_1
WR 16 = HD 86161	6412-6443 (I)	8.283 ± 0.018	8.331 ± 0.018	8.809 ± 0.019	9.011 ± 0.022	0.048 ± 0.007	0.429 ± 0.011	-0.276 ± 0.008
	6476-6519 (II)	8.275 ± 0.014	8.325 ± 0.013	8.811 ± 0.015	9.006 ± 0.021	0.050 ± 0.005	0.436 ± 0.009	-0.291 ± 0.008
	6581-6589 (III)	8.240 ± 0.021	8.310 ± 0.015	8.768 ± 0.018	9.088 ± 0.022	0.070 ± 0.006	0.388 ± 0.009	-0.138 ± 0.008
HD 86000 (= c_1)	6412-6443 (I)	8.134 ± 0.009	8.146 ± 0.010	8.268 ± 0.011	9.013 ± 0.015	0.011 ± 0.006	0.110 ± 0.005	0.623 ± 0.006
	6476-6519 (II)	8.125 ± 0.008	8.136 ± 0.008	8.258 ± 0.010	9.000 ± 0.012	0.011 ± 0.005	0.111 ± 0.005	0.620 ± 0.005
	6581-6589 (III)	8.121 ± 0.007	8.137 ± 0.007	8.255 ± 0.008	9.004 ± 0.009	0.016 ± 0.004	0.102 ± 0.004	0.631 ± 0.004
HD 85810 (= c_2)	6412-6443 (I)	7.951 ± 0.008	7.936 ± 0.010	8.015 ± 0.011	8.642 ± 0.014	-0.015 ± 0.005	0.094 ± 0.005	0.548 ± 0.005
	6476-6519 (II)	7.939 ± 0.007	7.926 ± 0.008	8.004 ± 0.009	8.627 ± 0.012	-0.013 ± 0.004	0.091 ± 0.005	0.545 ± 0.004
	6581-6589 (III)	7.935 ± 0.006	7.927 ± 0.007	8.000 ± 0.008	8.629 ± 0.008	-0.008 ± 0.004	0.081 ± 0.004	0.556 ± 0.004

**Fig. 1.** The light and colour curves of WR 16 (= HD 86161) relative to the comparison star HD 86000 as a function of Julian Date in epoch I. The error bar ($\pm \sigma$) is shown in the left top corner

jump like the type between epochs II and III, also occurred in the Strömgen photometric data set of WR 6 (WN 5) (van der Hucht et al., 1989). However, it is unknown whether the change of WR 16 happened gradually or suddenly. It is not very likely that these effects are caused by an observational problem, say by a wrong filter system. This conclusion is based on the fact that during the jump of WR 6 at J.D. 2446498, nothing happened with the light detected from WR 16 (see Fig. 2). Besides, the way in which the

fluxes in three of the four bandpasses vary (see the end of this section), suggests a physical cause.

The y curve shows several waves with a time scale of the order of 10^d , which reminds one of the period claimed by Moffat and Niemela (1982) and Lamontagne and Moffat (1987), but which does not fit at all (see Sect. 5). The total range amounts to $\sim 0^m06$.

Similar to the WN 5 type star WR 6 (van der Hucht et al., 1989), $b-y$ is red if the star is bright and vice versa. Further, also here $b-y$ and $v-b$ are in antiphase with each other. The correlation diagrams Figs. 3 and 4 illustrate this behaviour for epoch I. The same correlations are present in the data of the other epochs. The colour behaviour of the small time scale variations, thus those within a night or those from night to night are similar to those of the long time scale $\sim 10^d$ variations. Apparently they are caused by the same mechanism. The $u-v$ curve shows the smallest intrinsic scatter, thus in u and v the light variations are strongly synchronous.

It should be noted that the size of the jump between epochs II and III in the various photometric parameters fits the correlation diagrams in Figs. 3 and 4, as far as y , $b-y$ and $v-b$ are concerned. For $u-v$ the jump does not fit at all. Obviously something different happened with the flux in the band pass u , which dropped in contrast with the fluxes in the other band-passes.

4. The influence of the emission lines on the photometry

Figure 5 shows spectrophotometry of WR 16 by Jeffers and Weller (1985). The total width of the $uvby$ band passes is indicated by the bars near the horizontal axis. Strong emission lines of He and N are present in especially the b band and less in the v band. The y band is the least influenced. On the u band we only have spectrophotometric information up to 3600 Å (near the effective

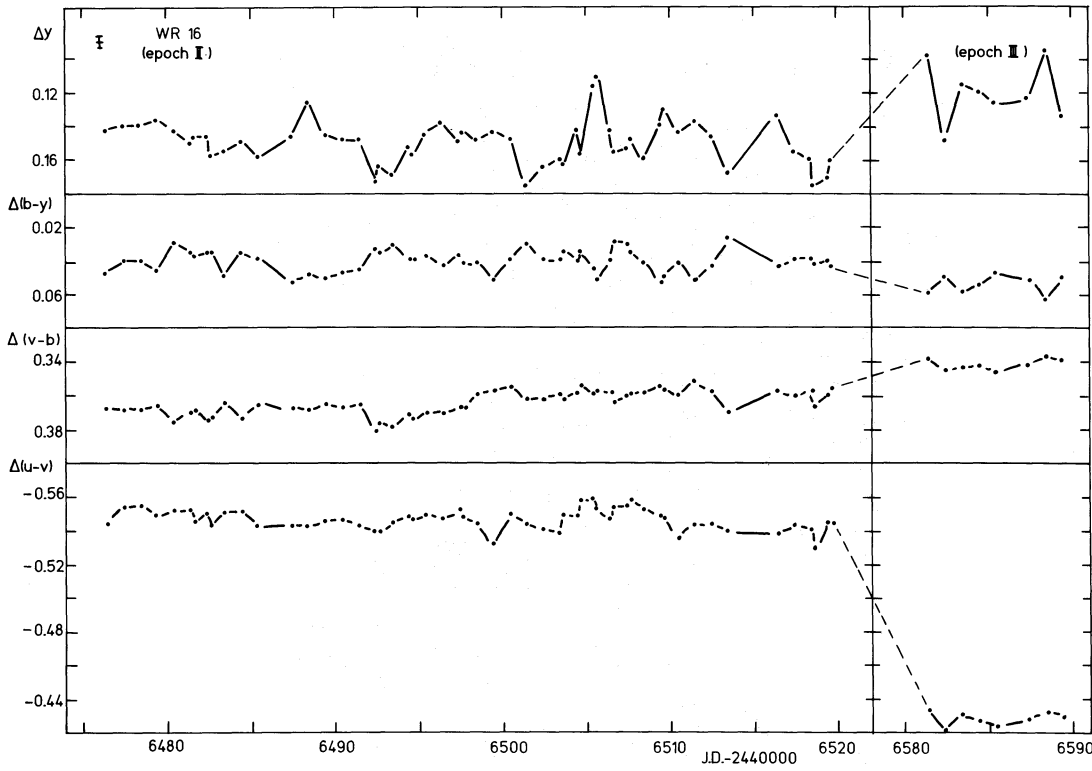


Fig. 2. The light and colour curves of WR 16 (= HD 86161) relative to the comparison star HD 86000 as a function of Julian Date in epochs II and III. The error bar ($\pm\sigma$) is shown in the left top corner

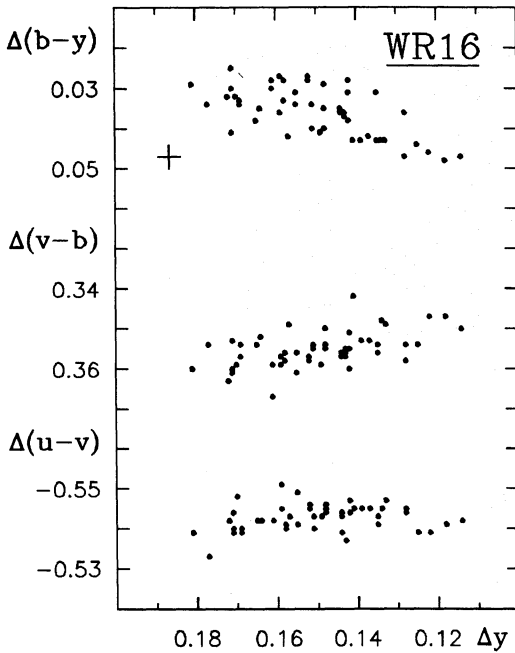


Fig. 3. The correlation diagram for Δy and the colour indices. The error cross for the data points is shown

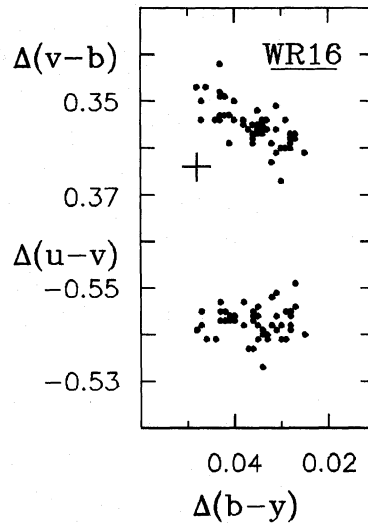


Fig. 4. The correlation diagram for $\Delta(b-y)$ and the two other colour indices. The error cross for the data points is shown

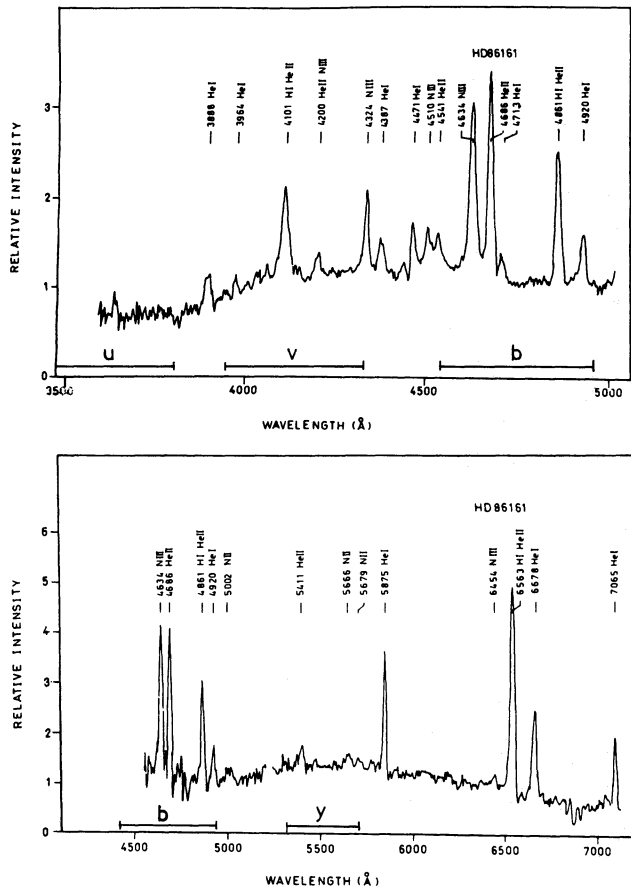


Fig. 5. Spectrophotometry of WR 16 by Jeffers and Weller (1985), showing the position of the uvby band-passes

wavelength) while the transmission curve extends down to 3400 Å. The emission lines are listed in Table 3. As a comparison we also show for two other WN 8 type stars (WR 40 and WR 156) a number of emission lines and their equivalent widths.

The anti correlation between the y and $b-y$ curves indicates that the light curve in b has a smaller amplitude. Indeed, the total range is $\sim 0^m045$, while in the other band-passes it amounts to 0^m055-0^m060 . Obviously continuum variations are responsible for the bulk of the light variations, while a constant He II 4686 line emission, or a He II 4686 line emission which varies little (equivalent width $\sim 20\%$ of the FWHM width of the b band), could be the cause that b varies always less than the other band passes. This is also the case with the jump between epoch II and III (see Sect. 3).

5. The search for a quasi-period (\bar{P})

The literature value for the period of the light variation amounts to 10^d73 , resulting in a double peaked light curve in the phase diagram with a large scatter (Moffat and Niemela, 1982). The interpretation is that it is caused by an ellipsoidal primary in a binary system. The 10^d73 period does not fit our data set.

Manfroid et al. (1987) demonstrate that the comparison star used by Moffat and Niemela is slightly variable. Besides, they claim to have found in their own photometric data made in the Strömgren b filter, the presence of two sine waves with different periods (1^d344 and 2^d55). The first one appeared to be detectable

in the data of Moffat and Niemela (corrected for the variability of the comparison star) and both more or less in the small number of data of van Genderen et al. (1987).

A comparison of Manfroid et al.'s predicted light curve (their Fig. 2) with the empirical one of our present data (Figs. 1 and 2) does not support the double sine variability. Our data in Figs. 1 and 2 rather suggest a one-peak light curve with a time scale of $\sim 10^d$ comparable with the analysis of Gosset et al., (1989) on the same data set (or its alias near 0^d9).

Balona et al.'s, (1989) data set obtained in 1988 even shows very clearly a one peaked light curve with a time scale of $15-20^d$. The quasi-period $\bar{P} = 17^d54$. Therefore it is likely that the star's brightness behaves differently from one time interval to the other, with a variable quasi-periodicity. In order to check this statement we analyzed our new data set (covering a time interval of $\sim 110^d$), excluding epoch III (because the average brightness level is different from the other two epochs), with Sterken's (1977) period search program. We only used the y data because the influence of emission lines is smallest in this band (Sect. 4).

The results of the search between 0^d2 and 20^d with steps of 0^d001 to 0^d01 resulted in a few possibilities of which the best one is $\bar{P} = 9^d280$ ($\nu = 0.1078 \text{ cd}^{-1}$, $r = 0.47$) and its alias $\bar{P} = 0^d9020$ ($\nu = 1.1086 \text{ cd}^{-1}$, $r = 0.43$). Since the data exhibit a strong phenomenon of pseudo-aliasing with $\Delta\nu \sim 0.015 \text{ cd}^{-1}$, the second best $\bar{P} = 8^d160$ ($\nu = 0.1225 \text{ cd}^{-1}$, $r = 0.44$) is no more than a pseudo-alias of the best one ($0.1225-0.015 \sim 0.1078$). The aliases of $\bar{P} = 8^d160$ are $\bar{P} = 0^d890$ ($\nu = 1.1236 \text{ cd}^{-1}$, $r = 0.43$) a pseudo-alias of $\bar{P} = 0^d9020$ (see above) and $\bar{P} = 0^d471$ ($\nu = 2.1231 \text{ cd}^{-1}$, $r = 0.37$).

Quasi-periods, about half of the two best ones, are $\bar{P} = 4^d980$ ($r = 0.32$) and 3^d570 ($r = 0.32$), but they are of no significance.

Figure 6 shows the phase diagram for $\bar{P} = 9^d280$. Epoch I and epoch II are indicated with different symbols. The light curve is single peaked (amplitude 0^m025), with a large intrinsic scatter ($\pm 0^m03$).

The discussion above on light curve shape Sect. 3 and periodicity does not support the idea that the light variability is caused by an ellipsoidal star, or by a double mode, a conclusion similar to the one of Gosset et al. (1989). The variability is obviously not strictly periodic.

6. Discussion and conclusions

The explanation for the continuum variations must be sought in variations of the photospheric or pseudo-photospheric light (the layer in the dense envelope from where we receive most of the light). Since a rotating envelope tends to be concentrated near the equatorial plane of the star, the area near the poles must be thinner and consequently could offer more chance to have a temporarily view on a possible variable photosphere. Other possibilities are rotation modulation of a non-uniform illuminated pseudo-photosphere of which the patchiness can be more or less stable for several months. Daily variations in the number, size of strength of the patches could then explain the large intrinsic scatter of the quasi-periodic behaviour. Possibilities for this patchiness could be hot bubble ejections (Moffat et al., 1988; van Genderen et al., 1989), or sudden appearances of places with a much lower opacity (say by eddies), which can reveal a view into the lower and hotter parts of the envelope (van Genderen et al., 1987). Temperatures of the photosphere are expected to be $\sim 100000 \text{ K}$ (Stothers and Chin, 1979; Maeder, 1985) or even higher (Langer, 1989).

Table 3. Emission lines of the WN 8 stars WR 16, WR 40 and WR 156 in the Strömgen # 4 filters

Filter lambda c fwhm	Contributing lines			EW (Å)			
	Major	Minor	Mult. No.	WR 16 1976 CLP	WR 16 1974 JW	WR 40 HJS	WR 156 S & K
<i>u</i>							
3445							
3240–3650		N IV 3478.7	1				
		N IV 3483.0	1				
		N IV 3485.0	1				
		He I 3613.6	6				
		He I 3634.3	28				0.6
<i>v</i>							
4120							
4020–4190		He I 4019.1	..			0.9	
		He I 4026.2	18			3.2	2.2
		N IV 4057.8	3	5.1		2.5	1.4
	N III 4097.3	He II 4100.0	1 12		24.5	14.4	9.4
	N III 4103.4		1				
	Si IV 4116.1		1			8.9	5.6
<i>b</i>							
4730							
4630–4820	N III 4634/41		2	27.5	38.9	55	20.9
	He II 4685.7		1	30.9	38.1	57	23.3
		He I 4713.2	12		5.7	5.0	1.7
<i>y</i>							
5520							
5380–5630	He II 5411.5		2	3.2	11.4	9.6	

References: HJS = Smith, 1955; S & K = Smith and Kuhl, 1981; CLP = Conti, Leep and Perry, 1983; JW = Jeffers and Weller, 1985

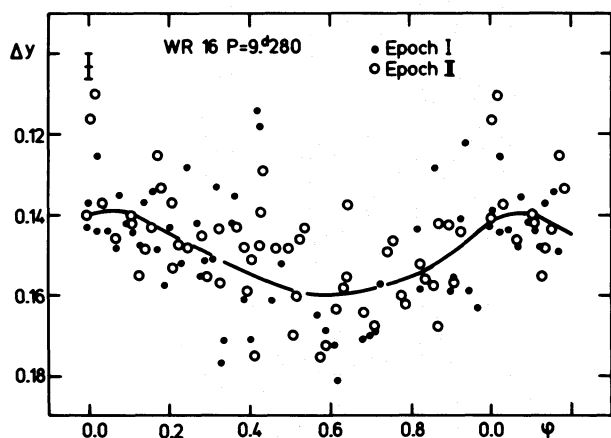


Fig. 6. The phase diagram for WR 16 with $P = 9^d280$ using the data of epochs I and II

The jumps in brightness, whether gradual or fast (like once observed in WR 6, van der Hucht et al., 1989), are not a matter of continuum variation only, in view of the different directions in which the various fluxes, *u*, *v*, *b* and *y* vary. Consequently strong changes in emission line strengths must be at least as important. Apparently, conditions in the envelope, presumably on a local scale, can change strongly.

The observations in epoch III do not contradict the quasi-period of 9^d280 , although the brightness level rose in *y* by $\sim 0^m04$. However, the number of observations is small, so that we cannot make any definite conclusion on the stability of the quasi-period and the light curve characteristics, after the photometric jump.

Our conclusion on the importance of the continuum variations and the secondary role of the emission line variations is in agreement with the results on other WN type stars by van Genderen et al. (1987, 1989, *VBLUW* photometry) and van der Hucht et al. (1989, *uvby* photometry).

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