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An investigation of the micro-variations of highly luminous OBA type stars. II*

A.M. van Genderen

Leiden Observatory, Postbus 9513, NL-2300 RA Leiden, The Netherlands

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Summary. The micro variations of six high-luminous O- and two B-type stars are investigated. The *VBLUW* photometry is described in Paper I (van Genderen et al., 1985). Temperatures, gravities and reddenings are determined with the aid of theoretical colours. At least six stars of this sample, main sequence stars as well as evolved ones, show a periodic or quasi-periodic oscillation in the light curve, while they also show a second type of non-periodic variation superimposed on the mean light- and colour curves (called δ variations). Large convective elements in the atmosphere with varying physical conditions could be largely (for the O type stars) or partly (for the B type stars) an explanation. The δ variations in the light- and colour curves of the two B type stars may be largely caused by a non-regular pulsation. One nitrogen rich star O type star HD 105056 shows the same periodicities in the radial velocity and photometric variations, suggesting that pulsation is the cause. Cyclic variations in the colour curves are scarce, especially for the O type stars. The expected amplitudes are a factor of 10–20 smaller than the light amplitudes. Thus they may be wiped out by the δ variations in most cases, which have ranges in the colours sometimes a factor of two larger. The amplitudes of the light variations, ranging from 0.01–0.08 mag, decrease the hotter the stars are.

All periods are much longer, up to a factor of 10, than the theoretical pulsation periods for the radial fundamental mode. Non-radial pulsations are likely the cause. The observations of the hottest stars ($T_{\rm eff}\sim 40$ and 50,000 K) suggest that even their photospheres are unstable against convection or that they pulsate, contrary to theoretical models.

Key words: early type stars – supergiants – variable stars – photometry – oscillations

1. Introduction

Pioneering work on the photometric stability of a large number of high-luminous stars have been conducted by Maeder and Rufener (1972) baed on a statistics of Geneva photometry. Their main results are that the amplitudes of the variations increase with luminosity and with decreasing temperatures. The variations are smallest for the O type stars, with amplitudes $\leq 0\overset{\rm m}{.}02$, while a maximum is reached near the B type supergiants (Burki 1978). Appenzeller (1972) found a similar trend for the LMC supergiants.

Long term photometric observations of B to G type supergiants revealed cyclic, but not strictly periodic variations. These time scales, called characteristic periods and in this paper written as $\bar{P}$, obey a *PLC* relation suggesting that the main mechanism is pulsation (Maeder and Rufener, 1972; Sterken, 1976, 1977; Burki, 1978). A new sample of B and A type supergiants has been observed and analyzed by Percy and Welch (1983). Schild et al. (1983) analyzed the magnitudes and colours of a large number of early type Ia supergiants, using the data from different catalogues. They found brightness variations with typical amplitudes of $\sim 0\overset{\rm m}{.}1$. Stagg (1983) observed six B type stars in the *B* band and found micro variations on a time scale of a day or so. Underhill (1984) found with IUE small photometric variations in the far ultraviolet of four OB type supergiants.

Lovey et al. (1984) computed theoretical radial pulsation periods for high luminosity stars and compared them with the observations. It appeared that 40 % of the observed $\bar{P}$'s agree with the fundamental mode of pulsation, while the other ones are 1.5 to 4 times longer. Non-radial oscillations connected with convection as well as post-red supergiant evolution may be responsible for the longer periods. Evolved stars have a stronger mass concentration towards their center and a smaller average density, which causes a longer fundamental period as compared with less-evolved stars of the same mass. In addition part of the oscillations may be in the radial mode, others in the non-radial mode (Maeder, 1980; Lovey et al., 1984), or only the outer mantle pulsates.

The possible presence of bi-polar regions on hot stars connected by magnetic loops and coronal-hole type regions in the atmospheres (Underhill, 1983b; Underhill and Foley, 1984) may be another source of micro variations.

In the light of these theories it is of most importance to investigate the stability of the hottest luminous stars with great accuracy. We present here a discussion of characteristic periods and amplitudes of light- and colour variations of the micro variations of six high-luminous O type and two B type stars. The observational technique and the observations are discussed by van Genderen et al. (1985, hereafter called Paper I).

Send offprint requests to: A.M. van Genderen

* Observations collected at the ESO, La Silla, Chile

Table 1. Reddenings and some physical characteristics of the program stars. (Data without notes are from this paper)

HD/HDE	$E(V–B)$ (log int)	$E(B–V)_J$ (mag)	M_{V_J}	$T_{\rm eff}$	$\log T_{\rm eff}$	$M_{\rm bol}$	$\log L/L_\odot$	$\log g$	$R/R_\odot$	Remarks
37022	0.087	0.21	−4.1	35,000	4.544	−7.5	4.90	4.5	8	HR 1895
		0.37[e]		38,500[a]	4.858[a]	−8.06[a]	5.12[a]			
57061	0.043	0.10	−6.9	29,000	4.462	−9.6	5.74	3.5	30	Binary: O9.5+$g^{\rm g}$
		0.16[e]	−7.0[e]							HR 2782
62150		0.57[c]	−6.7[b]	15,000[b]	4.176[b]	−7.9[b]	5.06[b]	2.4[b]	50[b]	$M/M_\odot=24^{\rm b}$
	0.238	0.56	−6.9[h]	14,500	4.161	−8.1	5.15	2.0	66	
76556	0.286	0.67	−5.2	40,000	4.602	−9.2	5.59	4.0	13	
		0.71[c]	−5.3[e]	42,000[a]	4.623[a]	−9.14[a]	5.56[a]			
93205	0.151	0.36	−5.9	50,000	4.699	−10.5	6.11	4.5	16	Binary[e], $R=4.0^{\rm f}$
		0.38[c]								
96248	0.170	0.40	−6.2	21,500	4.332	−8.2	5.19	2.5	30	
		0.37[e]	−6.1[e]							
105056	0.135	0.32	−6.5[d]	30,500	4.484	−9.5	5.70	3.5	26	
				35,000[i]						
305523	0.176	0.42	−5.3	32,000	4,505	−8.3	5.22	4.0	13	$R=4.0^{\rm f}$
		0.49[c]								

[a] Garmany et al. (1982)
[b] Leitherer and Wolf (1984)
[c] Thé and Groot (1983)
[d] Average brightness for hot supergiants
[e] Humphreys (1978)
[f] Abnormal extinction law according to Thé et al. (1980)
[g] IUE Low Dispersion Spectra, Atlas Part 1 (1984)
[h] Distance modulus 12.92 of Humphreys (1978)
[i] Underhill (1984)

2. The reddenings and the physical parameters

Reddenings were derived with the aid of the theoretical two-colour diagrams based on computations by Lub and Pel (1983) using the model atmospheres of Kurucz (1979). In these diagrams, the stars were shifted backwards along the reddening line onto the relations for constant gravities viz. $\log g = 2.0$, 2.5, etc. resulting in different reddenings for different gravities. The observed colours were taken from Table 3 of Paper I. The slopes of the reddening lines are $\frac{E(B–L)}{E(V–B)} = 0.38$, $\frac{E(B–U)}{E(V–B)} = 0.56$ and $\frac{E(U–W)}{E(V–B)} = 0.34$, based on the extinction law $A_{VJ} = 3.1\,E(B–V)_J$ (Barlow and Cohen, 1977). Although two stars have clearly a deviating extinction law viz. $R = 4.0$ (HD 93205 and HDE 305523) according to Thé et al. (1980), we did not correct the slopes of the reddening lines. The reasons are the uncertainties in the shape of the extinction curve in the ultraviolet part of the spectral energy distribution and in the theoretical colours. We estimate that the error introduced by adopting $R = 3.1$ for these stars is much smaller than the error introduced by the two uncertainties just mentioned, which we estimate to amount to ± 0.015 in $E(V–B)$.

Then the observed colours were corrected for the different reddenings based on the various gravities. By comparing the four corrected colour indices with the theoretical colours as a function of $T_{\rm eff}$, temperatures could be derived for each colour. The reddening resulting into the most consistent values for the four temperatures was chosen as the best value. Often the $T_{\rm eff}$ derived from $U–W$ deviated too much from the other three temperature determinations and therefore it is not always used for the average value listed in Table 1. This table also lists the corresponding reddening and gravity. The estimated uncertainties in $T_{\rm eff}$, $\log g$ and $E(V–B)$ are ± 1000 K (for the cooler stars), $\pm \leqq 3000$ K (for the hotter stars), ± 0.5 and ± 0.015, respectively.

$E(B–V)_J$ is derived by multiplying $E(V–B)$ with a factor 2.375–0.169 $(V–B)$, in which $V–B$ is the observed colour (Pel, 1982). Absolute magnitudes were derived using the reddenings from Table 1 and using $R = 3.1$, with the exceptions of the two stars mentioned above for which $R = 4.0$ and using the current cluster distances. Values for the radius were computed from $M_{\rm bol}$. All these particularities are also listed in Table 1.

3. The search for the characteristic periods

In order to find characteristic periods $\bar{P}$, we used the method applied by Sterken (1977) to variable supergiants. This method determines the optimal characteristic period $\bar{P}$ by a method of least squares fitting in an harmonic data analysis. First we determined for each star in which period interval the search for $\bar{P}$ should be performed. Generally the intervals were taken from $0^{\rm d}1$ up to a week or more with steps of $0^{\rm d}01$. Only in the case of HD 62150 steps of $0^{\rm d}1$ were small enough in view of the long time scale of its

Table 2. Characteristic periods and amplitudes. Stars tabulated in order of decreasing T_{eff}

HD/HDE	Sp^a	$\overline{P}$ (*d*)	r θ	P'_{rot} (*d*)	Ampl. V (log int.)	Ampl. V_J (mag)	Remarks
93205	03V	2.17 2.16	0.65 0.58	5.4	0.0046	0.012	$v \sin i = 150^c$
76556	05.5 V Nf	0.91 0.91	0.61 0.52		0.0045	0.011	
37022	07.0 V			3.2	0.0050	0.013	Secular increase $v \sin i = 98^c$, 127^d
305523	O9 II	(5.51) (5.51)	0.53 0.73		0.0030	0.008	
105056	O9.7 IaeN	2.35/1.73 2.33/1.75 2.322[b]	0.66/0.65 0.38/0.50	13.9	0.0230	0.058	$v \sin i = 40^c$, 95^d
57061	O9 I	1.76 1.795	0.79 0.41	13.6	0.0200	0.050	$v \sin i = 75^c$, 112^d
96248	B1 Iab	8.80 8.76	0.81 0.39	16.6	0.0230	0.058	$v \sin i = 92^d$
62150	B3/5 Iab	45.0 44.8	0.63 0.60		0.0300	0.075	

[a] If more spectral classifications are known (Paper I), then only one of them is given.
[b] Best period according to Walborn et al. (1980) based on radial velocity variations (see Sect. 3)
[c] Conti and Ebbets (1977)
[d] Uesugi (1976)

principal variations. Then the highest peak was selected in the spectral function R by visual inspection, delivering the best value for $\overline{P}$. This one was used to construct the phase diagrams. We applied this search for $\overline{P}$ on the brightness V only. Table 2 lists the values for $\overline{P}$ and the correlation coefficients r (stars are tabulated in order of decreasing temperature). In the case that two peaks differ only slightly in height, two phase diagrams were constructed in order to compare them with each other. Table 2 lists then two values for $\overline{P}$ and r, of which the first one is prefered.

Then all periods were checked by applying the dispersion minimization technique of Stellingwerf (1978), which is a generalization of the Lafler-Kinman (1965) technique. This method seeks to minimize the dispersion of the data at constant phase and is also well suited for irregularly spaced data and for non-sinusoidal time variations. A bin structure 5, 2 was used. Usually the intervals in which the search was made were taken as follows: $0^d.1$–$1^d.0$, $1^d.0$–$2^d.0$, etc. The size of the interval influences the value of the statistic θ and sometimes also the value of the best period. The smaller the intervals are taken, the smaller θ of the best period can become. For example: in the interval $1^d.0$–$2^d.0$ we found for HD 57061 $\overline{P} = 1^d.76$ and $\theta = 0.52$, but in the interval $1^d.7$–$1^d.9$, $\overline{P} = 1^d.795$ and $\theta = 0.41$ (which is listed in Table 2).

All periods found with Sterken's method were confirmed. Usually the differences are small, see Table 2, in which $\overline{P}$ found with Stellingwerf's method is listed below that of Sterken's one. Also θ is listed (θ and r run in opposite directions, when $r = 0$, $\theta = 1$ and vice versa).

A few remarks on the results and on individual stars should however still be made. The average correlation coefficient r for six program stars amounts to 0.69, which is practically equal to that of Sterken's (1977) B type supergiants viz. 0.71. HDE 305523 is omitted because of its low r value (0.53). Also with Stellingwerf's method the best period was $5^d.51$, but θ is not very significant either. Therefore the reality of the cyclic behaviour may be doubtful. Consequently it is bracketed in Table 2.

For HD 57061 we have found two possible periods with Sterken's method viz. $0^d.39$ and $1^d.76$ ($f = 2.564$ and $0.568\,\mathrm{cd}^{-1}$, respectively) with nearly similar r values (0.79). Since the first period had an insignificant θ value with respect to the second one according to Stellingwerf's method, we listed only the second period (see above). A third period $\overline{P} = 0^d.64$ ($f = 1.566\,\mathrm{cd}^{-1}$) has $r = 0.70$ and $\theta = 0.51$ (in the interval $0^d.5$–$0^d.8$), thus is also of less significance than the longer period.

It is of interest to mention the result of the nitrogen rich star HD 105056 (09.7 Iae N), which was already noted to be variable by Cousins (1972). Underhill (1984) found light variations in the far ultra violet with the IUE satellite of the order of $\sim 0^m.1$. Radial velocity observations were analyzed by Walborn et al. (1980) with the Lafler-Kinman (1965) method. No period could fit all observations satisfactorily, but the one quoted by them which could be the best, is $2^d.322$ which is close to ours. We reanalyzed their measurements with the aid of the two methods described above and found the same possible periods as listed in Table 2: the first method gave a higher correlation coefficient for $\overline{P} \sim 1^d.7$ viz. $r \sim 0.65$, against $r \sim 0.60$ for $\overline{P} \sim 2^d.4$. The second method resulted into the opposite: $\overline{P} \sim 2^d.4$ was more significant with $\theta \sim 0.55$ than $\overline{P} \sim 1^d.7$ with $\theta \sim 0.60$. Consequently no unambiguous solution can be found with the available data sets (see for a possible double mode oscillation Sect. 5). An important conclusion however can be drawn: optical and radial velocity variations are obviously correlated, indicating that some kind of pulsation is the cause of the variations.

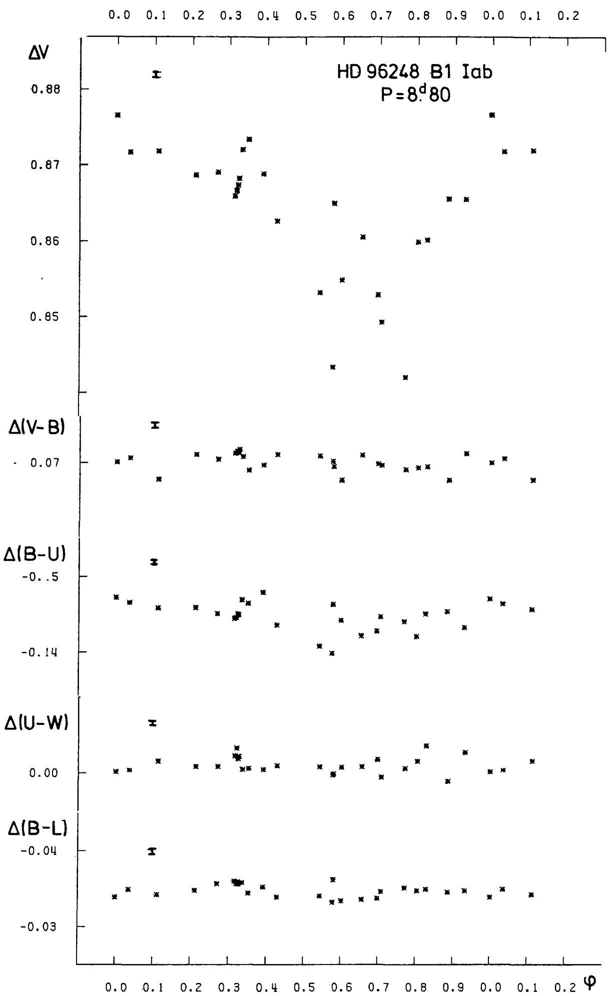

Fig. 1. The light- and colour curves of HD 96248 (B1 Iab)

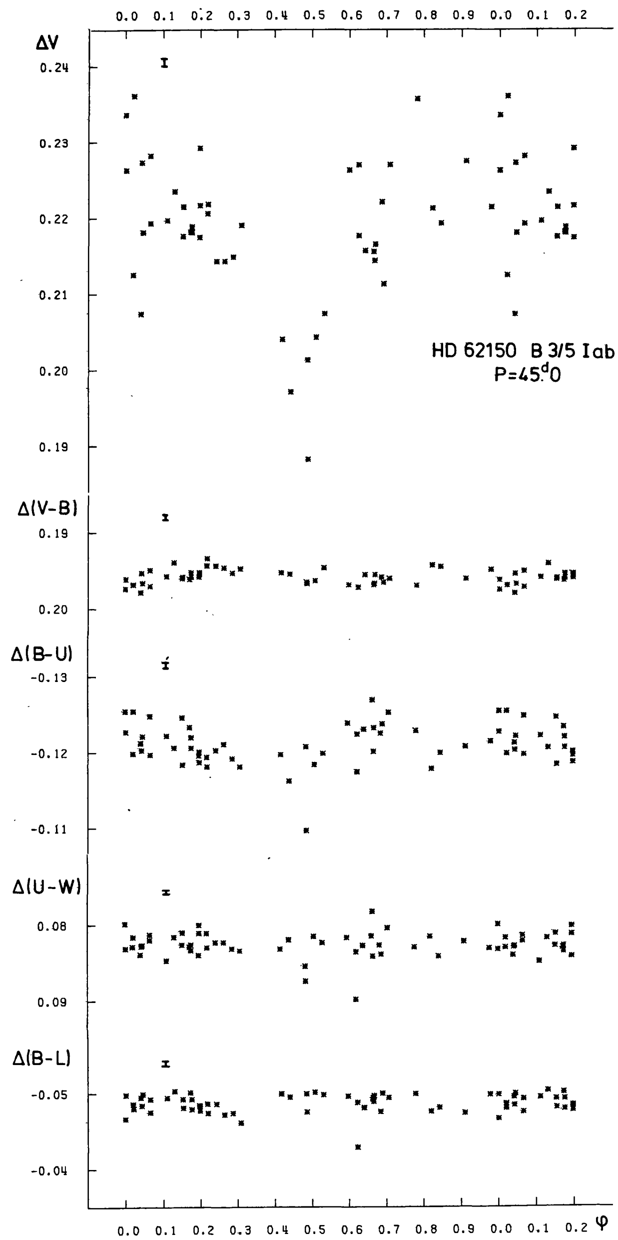

Fig. 2. The light- and colour curves of HD 62150 (B3/5Iab)

Figures 1–4 show the phase diagrams using the $\bar{P}$'s found with Sterken's method for the light variation of seven stars and also the colour variations for three stars. The colour variations of HD 96248 and HD 62150 are shown because some of them show a cyclic variation. *V–B* and *B–L* appear to run more or less in antiphase with *V* and *B–U*. The amplitudes are a factor 10–20 smaller than the light amplitudes. Those of HD 93205 are shown as an example of which the colour curves show no cyclic variations at all, presumably wiped out by the larger intrinsic scatter, which is presumably a factor of 2 larger than the expected cyclic colour amplitudes (Sect. 4). Notice that the vertical scales of the latter star are twice as large as for the other two stars. The other four stars of which we omitted the colour curves, show a similar scatter in the colour as for HD 93205. Some of them show an undefined cyclic variation, but much smaller than the total scatter. The average m.e. bars of ± 0.0004 for *V* and of ± 0.0003 for the colours are shown in all figures.

Table 2 lists the light amplitudes for *V* in log intensity scale and for V_J in magnitudes. The estimated uncertainty is ± 0.0010 and $\pm 0^m.003$, respectively. For the two B type stars the amplitudes are largest in the ultra violet passbands *U* and *W*. For the O type stars there is within the estimated uncertainty no obvious difference between long and short wavelength bands.

Figure 8 in Sect. 7 shows the amplitude/$T_{\rm eff}$ diagram. The amplitudes of the cyclic variations (or $\bar{P}$ variations) in the five passbands, ranging from 0.0030–0.0300, are indicated with *V*, *B*, *L*, *U*, and *W*. The amplitudes of the secular light variation of HD 37022 (Paper I) are encircled. Obviously the amplitudes increase with decreasing temperature. We shall discuss this diagram later in this paper again.

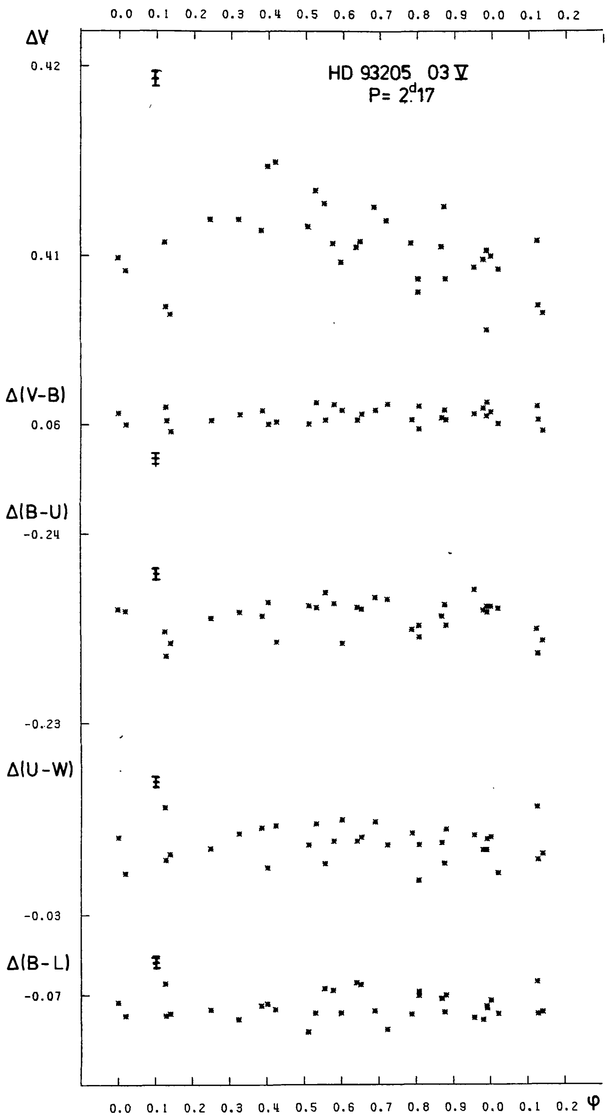

Fig. 3. The light- and colour curves of HD 93205 (O3V)

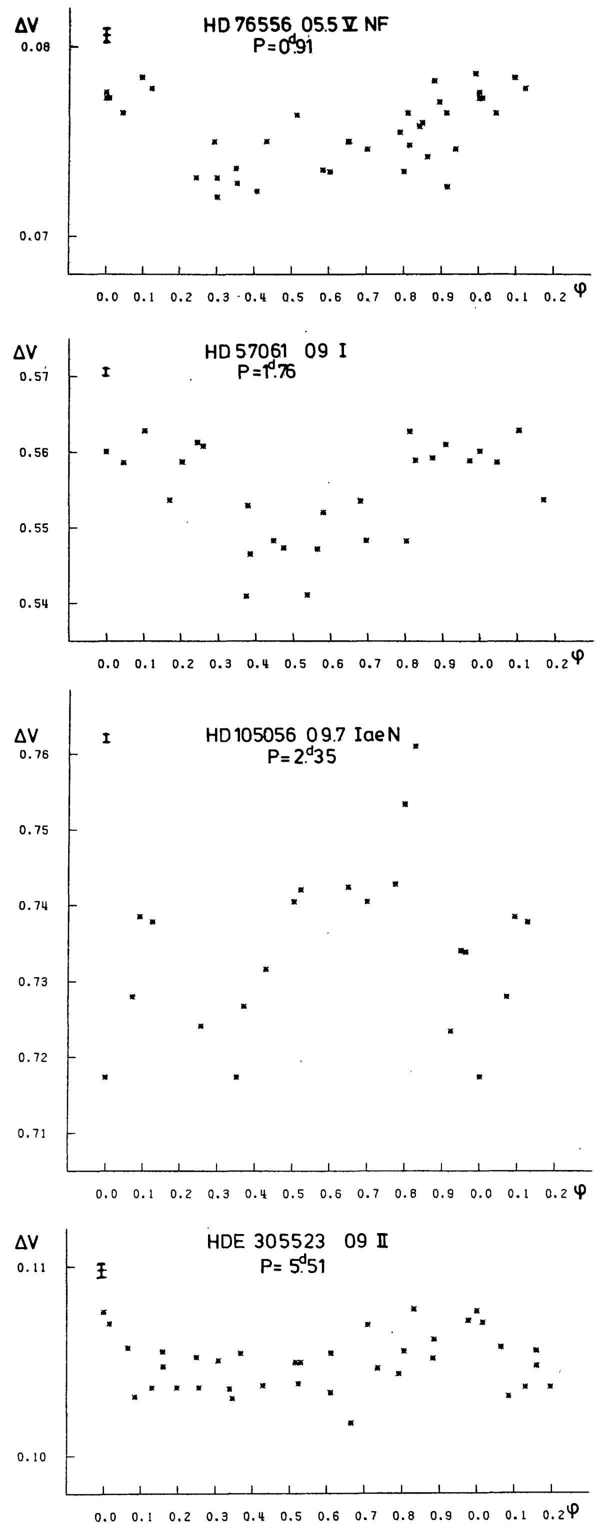

Fig. 4. The light curves of HD 76556 (O5.5V NF), HD 57061 (O9I), HD 105056 (O9.7IaeN) and HDE 305523 (O9II) in order of increasing $\overline{P}$

4. The stability of periods and cycles

All light- and colour curves (Figs. 1–4) show a considerable scatter amounting to at least five times the m.e. HD 37022 is the only star of which the scatter can be only attributed to the m.e. in the NA (Fig. 5 in Paper I). Apparently the scatter of the other stars is largely intrinsic.

At first sight it is not clear whether the intrinsic scatter is caused by say unstable periods and unstable shapes of the cycles, or by an additional mechanism of which the light variation is superimposed on the cyclic variation or by all of them. Therefore it would be of importance to know how stable the periods and cycles are, not only in the long run, but also from cycle to cycle.

In a number of well observed later type variable super- and hypergiants, the scatter increases in the phase diagrams the more cycles are used, say in the order of a few tens. For example HD 33579 (A2Ia$^+$) (van Genderen, 1979), HD 160529 (A2Ia$^+$) (Sterken, 1981) or BL Tel (F) (van Genderen, 1983). An important characteristic of these and other later type stars is that the light curves of individual cycles show little or no intrinsic scatter, while this is not necessarily the case for early type stars. The number of cycles which lies between the observations of most of our O type stars are sometimes a few hundred. This could therefore be considered as the reason for the large intrinsic scatter. However, we found real variations from night to night, which scatter around the mean light curves of the B type stars and even in a night within time intervals of a few hours only (Paper I). In view of the distribution of the NA in subsequent nights around the mean light curves of the O type stars, also favours the existence of variations on a time scale shorter than the length of the cycle. However, it should be confirmed by long runs in a night.

Thus it is possible that the intrinsic scatter is caused partly or mainly by another mechanism superimposed on the cyclic variation and not only by a variable period or light curve shape. [However it is still possible that part of the scatter is caused by intrinsic variations of the comparison stars of which it is not certain that they are completely constant stars (see Paper I). This should actually be settled by comparing them with other nearby stars.] We shall call the intrinsic scatter in the phase diagrams "δ variations".

5. A search for double modes and for a periodicity in the light variation of two massive X-ray binaries

In Sect. 4 we mentioned a few possibilities which increase the scatter in the phase diagrams, but double modes can be also considered as a source for that. In order to investigate whether the δ variations are caused by the presence of a second period (P_1), the principal oscillation ($\bar{P} = P_0$) was removed from the data before the search for weaker modes was done. Usually Stellingwerf's method was applied, but for the stars with the largest δ variations, also that of Sterken was used.

Perhaps with the exception of HD 105056, none of the stars seems to possess a second mode. For HD 105056 we found using our photometric material $P_1 \sim 3\overset{d}{.}7$, $\theta \sim 0{,}5$ and using the radial velocity variations of Walborn et al. (1980) $P_1 \sim 3\overset{d}{.}5$, $\theta \sim 0.55$. Similar to the search for the principal mode (see Sect. 3), both data sets resulted into comparable results. Since the θ values are marginal significant, no definite conclusions can be made until new and larger data sets are analyzed.

However the question is whether our data are really sufficient enough to rule out the presence of more periods by using these two methods. In Sect. 6 we find a tentative indication that only one period may be present.

We also investigated the intrinsic scatter around the mean orbital light curves of the well observed massive X ray binaries HD 77581 (Vela X-1) with a B0.5Ib primary (van Genderen, 1981) and HD 153919 with a O6.5I primary (van Genderen and Windhorst, 1981). The m.e. of the NA are at least twice as large as for the program stars, but well enough to apply the same analysis.

The result is that no cyclic variation at all is present. Although both binary OB companions have a different evolutionary background than the program stars (e.g. van den Heuvel, 1983), we presume that the fluctuations could be caused by some type of stochastic mechanism, perhaps related to those of the normal OB type highly luminous stars. They also have time scales of hours to a day or so and the colours often tend to become bluer with increasing brightness, and the amplitudes of the fluctuations are of the same order as those of the program stars (see also Sect. 7 and Fig. 8).

6. A photometric analysis of the δ variations

The photometric behaviour of the δ variations is analyzed with the aid of scatter diagrams: δV versus the δ variations in the phase diagrams for the colour indices (called δ colours) and the δ colours versus each other. The purpose is to settle the question which of the δ variations are truly a separate mechanism, and which are caused by variable light curves and periods. In the first case we expect a different colour behaviour, in the second case a behaviour similar to that during a cycle.

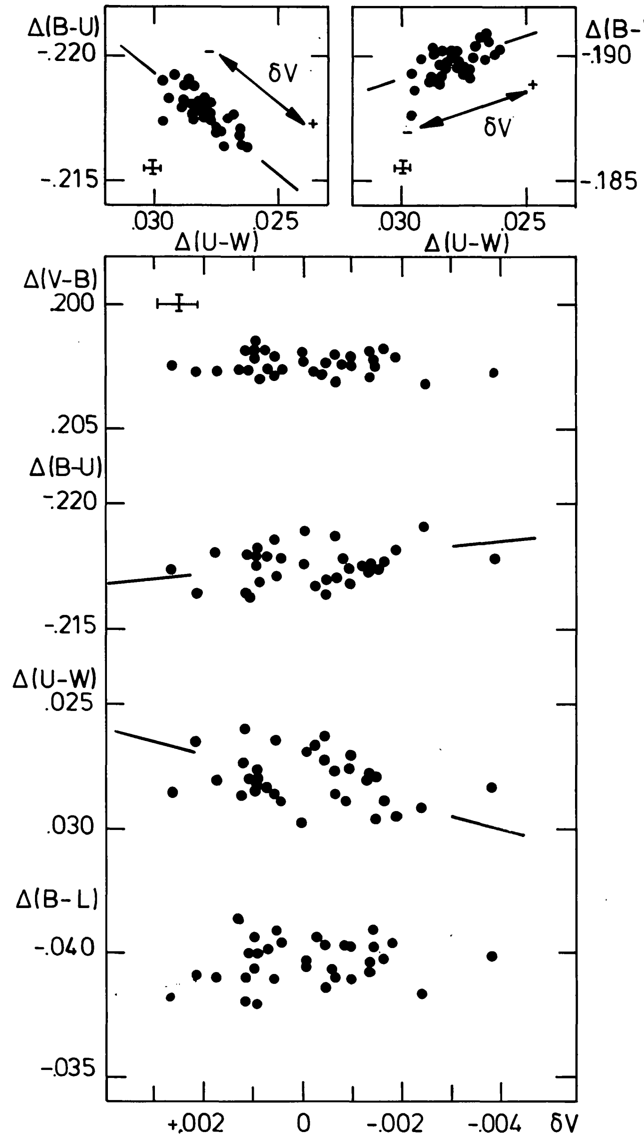

Fig. 5. A number of scatter diagrams for the δ variations of HD 76556 ($T_{\rm eff} \sim 40{,}000$ K). If the colour indices relative to the comparison stars (called Δ) did not show any cyclic behaviour, it was not necessary to derive the scatter around the average colour. The error bars represent the average m.e. of the NA of ± 0.0004 in V and ± 0.0003 in the colour indices

Figures 5–7 show a few examples. Notice that in case a cyclic behaviour is absent, the colours relative to the comparison star are plotted (called Δ) instead of δ. In the δV versus δ colour diagrams, a brightness increase runs upwards and blue is to the right. In the δ colour versus δ colour diagrams blue is at the top and to the right. The average mean error bars of ± 0.0004 in V and ± 0.0003 in the colours are shown at the left. The total vertical spread in say the $\delta V/\Delta(B-U)$ diagram, is equal to the total range of $\Delta(B-U)$ in the upper left diagram (viz. ~ 0.0030).

Figure 5 shows for HD 76556 ($T_{\rm eff} \sim 40{,}000$ K) the $\Delta(B-U)/\Delta(U-W)$ and $\Delta(B-W)/\Delta(U-W)$ diagram at the top and the

$\delta V/\Delta$ colour diagrams below. First we shall discuss the lower part of Fig. 5. The scale of δV is twice as large as for the colour variations. If δV is positive (brightness above the average light curve), $\Delta(B-U)$ is redder and $\Delta(U-W)$ bluer than the average colour and vice versa. This means for example that the variation in the U band usually takes place at a lower rate than in the B and W bands, or with other words that the amplitude of δU is on the average smaller than of δB and δW. The two short lines only based on eye inspection, roughly indicate the average trend of the δ colour with δV. In this way the average range of the δ variations can be read off: $\delta V \sim 0.0060$, $\delta B \sim 0.0060$ (since the variation in $V-B \sim 0$), $\delta U \sim 0.0050$ [since the average range in $\Delta(B-U)$] is ~ -0.0010, $\delta W \sim 0.0070$ [since the average range in $\Delta(U-W)$ ~ 0.0020] and $\delta L \sim 0.0060$. The true range in each pass band scatter around these values by 0.0020–0.0030.

The scatter in the colours $B-U$, $U-W$ and $B-L$ is twice as large as in $V-B$. Partly it must be intrinsic in view of the much smaller m.e. (see the error bars). This means that the *amplitude differences* of the δ variations in L, U an W are less constant from night to night than those in V and B. Thus there is a stronger synchronism between the variations in the V and B parts of the spectrum, than between those in the L, U, and W parts, containing Balmer limit, – jump and – continuum.

The characteristics of the relative amplitudes of the individual δ variations can be also studied with the aid of diagrams of the type shown at the top of Fig. 5. The average trend of δV is indicated by the arrows. This is however not more than an average, since the intrinsic scatter in the $\delta V/\delta$ colour diagrams is often large for $B-U$, $U-W$, and $B-L$. It appears that even if δV is large positive, $\Delta(B-U)$ can be too blue with respect to the average relation in the $\delta V/\Delta(B-U)$ diagram, the $\Delta(U-W)$ too red in the $\delta V/\Delta(U-W)$ diagram and vice versa. From the diagram at the left top it can be also read off that the flux in the U band varies at a lower rate than those in the B and W passbands, otherwise $\Delta(B-U)$ and $\Delta(U-W)$ would not show an opposite colour variation (reddening versus bluing and vice versa). The total range in $\Delta(B-U) \sim 0.0030$, reflects largely the vertical scatter around the average relation in the $\delta V/\Delta(B-U)$ diagram (~ 0.0020) and means that the *amplitude difference* of δU with respect to δB is variable. Thus if the brightness deviates from the average cyclic curve by a constant amount, the amplitude difference $\delta U-\delta B$ can vary by an amount as large as 0.0020 from one NA to the other. The amplitude difference $\delta B-\delta W$ is less variable in view of the small slope in the right upper diagram of Fig. 5: range in $\Delta(B-W) \ll \Delta(U-W)$.

The relation between brightness and colour residuals after assuming a single period, is perhaps a sign that these stars are subject to one oscillation only (Sect. 5). More observations should confirm this.

These amplitude differences differ from star to star. In Fig. 6 for example, we show apart from the same scatter diagrams as for the previous star, also the $\Delta(B-U)/\delta(B-L)$ diagram of the somewhat cooler star HDE 305523 ($T_{\rm eff} = 32{,}000$ K). In contrast with the same diagram of the previous star which is not shown, this one shows a clear correlation between the variations in the $B-U$ and $B-L$ colour indices. This means that the amplitude differences between the δB, δL and δU variations are stable. The δL and δU variations are larger than that of δB, thus therefore the colour indices $B-U$ and $B-L$ become bluer with increasing brightness and vice versa. The trend in the δV versus δ colour diagrams also differ in several respects from those of the previous star.

It appears that the amplitude differences between the δ variations in the five passbands are more irregular for cooler stars. This is illustrated in a few scatter diagrams of the star HD 62150

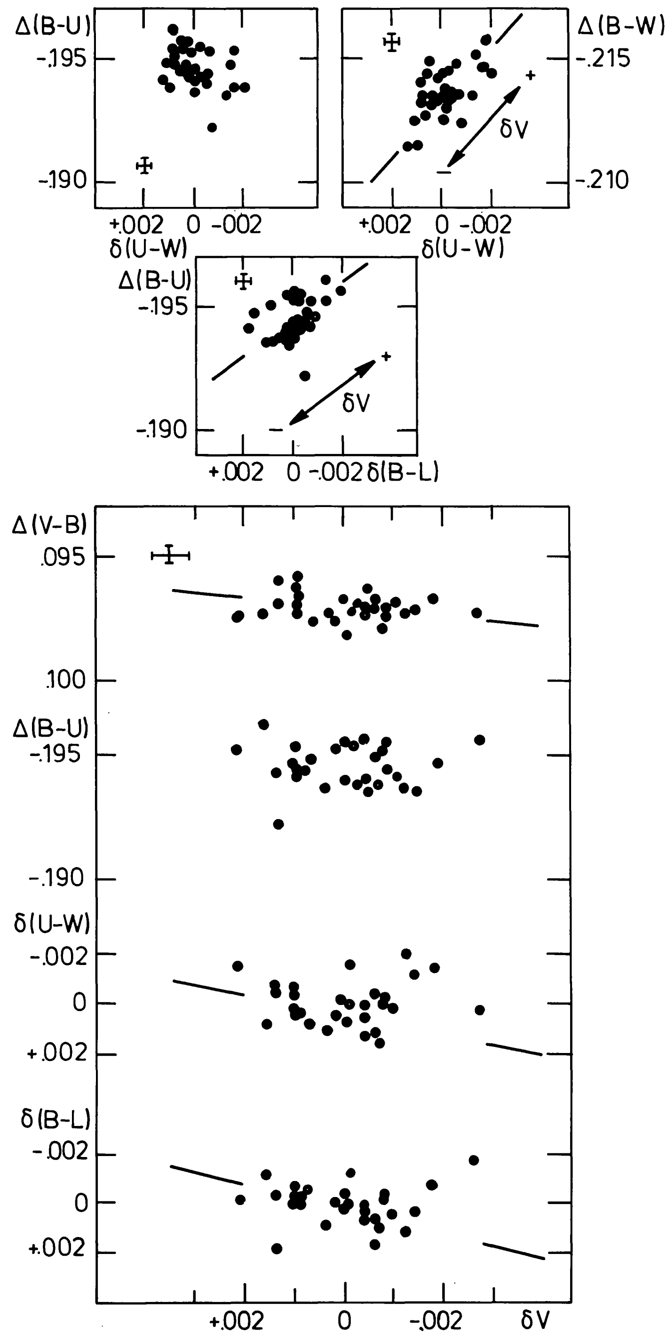

Fig. 6. The same as Fig. 5 but now for HDE 305523

($T_{\rm eff} = 14{,}500$ K) in Fig. 7. (Notice that the δV scale is twice as small as in Figs. 5 and 6.) The scatter is large indeed. In the $\delta V/\delta(B-U)$ diagram even twice as large as in the $\delta V/\delta(U-W)$ diagram. The total range of the scatter in $\delta(B-U)$ is ~ 0.0080, thus $\sim 2\frac{1}{2}$ times larger than for the O type stars. Since the Balmer lines and the Balmer jump are more prominent in cooler stars, these gradual increasing effects from O to B type stars could suggest the presence of moving cooler gas clouds of varying physical conditions.

All the cyclic light variable O type stars, lack clear cyclic colours variations (with a few exceptions such like the $V-B$ curve of the coolest O star in our sample HD 57061), while the δ variations often do show relative large colour variations (see Sect. 3). The latters

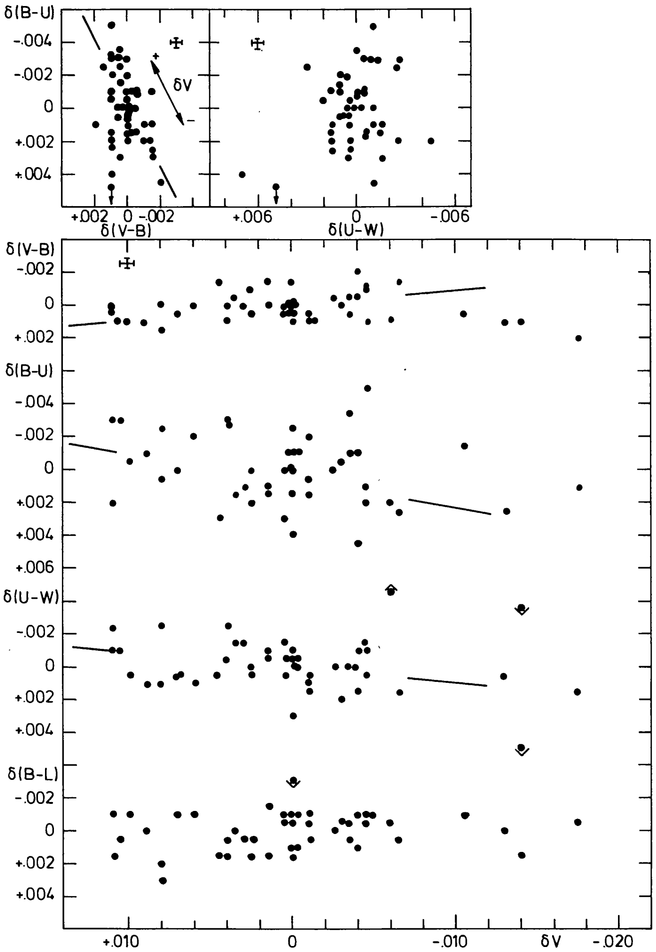

Fig. 7. The same as Fig. 5 but now for HD 62150

are in the range of 0.0010–0.0040. On the contrary, the B type stars more often show cyclic colour variations, while the scatter diagrams look more chaotic. Besides the trends in the $\delta V/\delta$ colour diagrams are similar to those of the cyclic colour variations. Thus for example $V-B$ and $B-L$ also run more or less in antiphase with V and $B-U$, similar to the cyclic colour curves.

These facts could be an indication that at least an important part of the δ variations of the O type stars are caused by moving cooler gas clouds of varying physical conditions expelled by active regions in the photosphere. Presumably those of the B type stars are mainly caused by variable cycles and pulsational effects at a smaller scale than the cyclic one. With respect to the latter supposition one can think of a convulsive type of pulsation, giving rise to bumpy variable light curves, which dominate the other intrinsic variations.

Here we arrive at the point that the boundary between the conception of pulsation and that of the possible presence of large convective elements moving up and down in an atmosphere, becomes more undefined. Perhaps we are dealing with a combination of both in view of the evidence summarized in Sect. 8, proving that the photospheres and atmospheres of early type supergiants are constantly in a state of unrest and turbulence, which seems to increase from O to B type stars. The δ colour variations, which become more chaotic from O to B type stars, support that.

7. The amplitudes of cyclic and δ variations

Figure 8 shows the amplitudes of the cyclic variations (also called $\bar{P}$ variations) and of the δ variations as a function of the stellar temperature (Table 1). The estimated uncertainties in the amplitudes are of the order of ± 0.0010 or $\pm 0\overset{m}{.}003$. They are indicated with the letters V, B, L, U and W, while these letters are preceded by a δ symbol for the variations. These δ amplitudes are estimated from the width of the scatter around the average light curves V, B, L, U, and W. For HD 37022, which only shows a secular variation, the letters are encircled.

What we already suspected from the work of Maeder and Rufener (1972) and Appenzeller (1972), is confirmed in Fig. 8, the hotter the stars the smaller the amplitudes of the variations. A surprising result is that the amplitudes of the δ variations seem to rise with those of the $\bar{P}$ variations and that they are roughly of the same magnitude.

We also plotted the amplitudes of the intrinsic variations of the OB type supergiant components of three X-ray binaries. The m.e. of their NA, although at least twice as large as those for the program stars discussed in this paper, are small enough to consider the scatter around the average light curve of the orbital revolution as largely intrinsic. The three stars are: SMC X-1 (van Genderen, 1974; van Genderen and van Groningen, 1981), HD 153919 (van Genderen and Windhorst, 1981) and HD 77581 (van Genderen, 1981). It appears that the amplitudes are of the same order as the normal OB type stars. The colour behaviour is more or less similar, hence the variations are largest at the short wavelengths. It is not possible yet to say to what extent the comparison with normal OB type is useful for the interpretation of these variations. After all the OB components in the X-ray binaries fill their Roche lobes more or less. Besides they have received a large fraction of their mass from the other component according to the models of conservative evolution of massive close binaries (e.g. van den Heuvel, 1983). It is of interest to mention that the amplitudes of the δ variations of these objects rise also with the amplitude of the light variation of the orbital revolution. This amplitude is a measure for the deformation of the massive component.

Burki et al. (1982) claim that the amplitudes of the intrinsic variations of the hypergiant ζ^1 Sco (B1 Ia$^+$) are correlated with their time scales: the larger the amplitude, the longer the timescale of the variation. Since our observing runs are not made in such long series of consecutive nights like Burki et al.'s observations, we cannot trace whether this is also the case for our stars.

8. Discussion

In order to investigate the possibility that the cyclic behaviour (the $\bar{P}$ variation) is caused by some persistent non-uniform surface brightness, say by spots or so, we temporarily adopt that $\bar{P}$ is equal to P_{rot}. The corresponding rotation velocity v is then found as follows. If

$$\bar{P} = P_{rot} = P'_{rot} \sin i$$

in which

$$P'_{rot} = \frac{2\pi R}{v \sin i}$$

the inclination i can then be found for those cases for which $v \sin i$ and R are known. Table 2 lists the values for $v \sin i$, sometimes two different values are known. R is listed in Table 1 and derived from

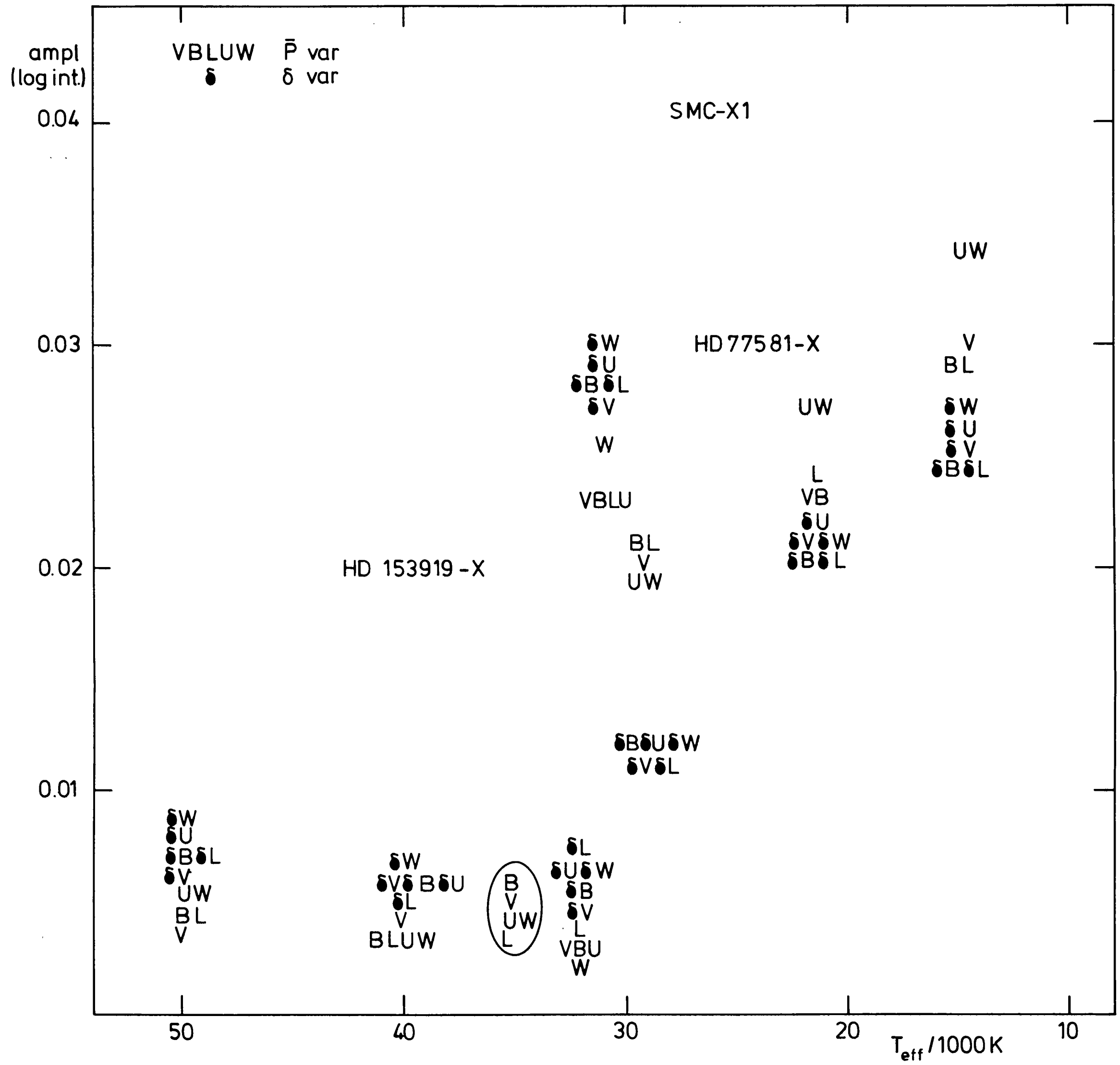

Fig. 8. The amplitudes in the five passbands of the cyclic- (or $\bar{P}$ variations) and of the δ variations as a function of the stellar temperature. The secular light variation of HD 37022 is encircled. The approximate position of the intrinsic variations of three OB supergiant components is X-ray binaries are also indicated

T_{eff} and L. Consequently, with i and $v\sin i$, v is known. It appears that HD 93205, HD 57061 and HD 105056 should have a rotational velocity presumably too high for normal OB type stars if our assumption of a spot mechanism is true: $v \sim 240$–$900\ \mathrm{km\,s^{-1}}$ of which two stars with $v > 370\ \mathrm{km\,s^{-1}}$. Thus with the exception of HD 96248, at least two stars have improbably high rotational velocities, if they are compared with the observed distribution of $v\sin i$ as a function of spectral type (Wolff et al., 1984). Thus it is more likely that the $\bar{P}$ variations are caused by some type of pulsation. The same conclusion has been made by Percy and Welch (1983) and Underhill (1984). The case of HD 105056 (Sect. 3) supports this.

In Fig. 9 we have plotted the program stars in the theoretical HR diagram adapted from Lovey et al. (1984). Theoretical P = const lines for radial pulsators in the fundamental mode (continuous lines) and empirical P = const lines (dashed lines) are shown with a few evolutionary tracks. The periods for our seven program stars are indicated. HD 37022, which lies close to the main sequence near $M \sim 30\,M_{\odot}$, has no cyclic variation. An "N" means that nitrogen lines are present in the spectrum. It is thus possible that these stars are in their post red super-giant stage (RSG), or that they were subject to a higher than normal mass loss rate during their main sequence life time (Dearborn and Eggleton, 1977).

It is obvious that the observed $\bar{P}$'s are much longer, sometimes by a factor of ten, than the theoretical ones for radial pulsators. This is in accordance with the result of a sample of OB type stars studied by Percy and Welch (1983). Lovey et al. (1984) found for a large fraction of B and later type stars a factor of four. They argue that non-radial pulsations connected with convection and post RSG evolution may be the cause of this discrepancy.

The fact that even the hottest stars ($T_{\mathrm{eff}} > 40{,}000$ K) of our sample are variable, could mean that also these stars have photospheres unstable against convection or that they pulsate. Theoretical models suggest that stars with $T_{\mathrm{eff}} > 35{,}000$ K should be stable against convection (Underhill, 1983a).

It would be of great importance to investigate how stable periods are. Further observations could settle this question. In this context it is of interest to mention that Baade and Ferlet (1984) claim to have found possible stable rotation-induced resonant coupling of two non-radial pulsation modes in γ Arae (B1 Ib).

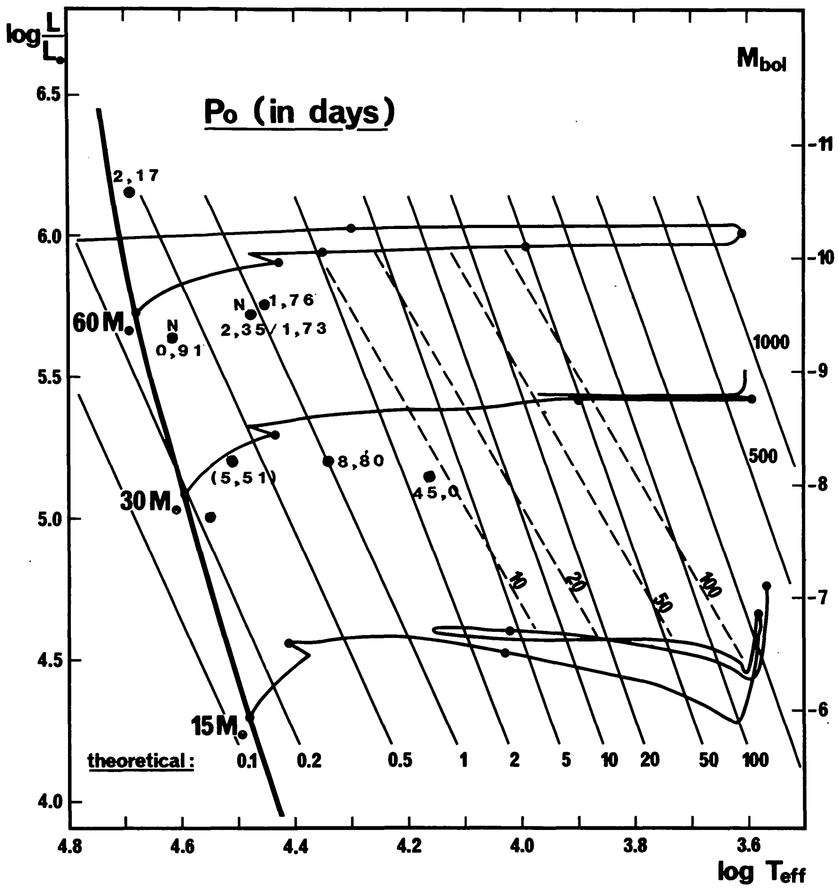

Fig. 9. The theoretical HR diagram with theoretical P = const lines (continuous lines) for the fundamental radial mode and the empirical P = const lines (dashed lines) adapted from Lovey et al. (1984). The eight program stars are indicated by dots. For seven stars the $\bar{P}$ is added. An "N" means that nitrogen lines are detected in the spectrum

The star HD 37022, close to the ZAMS, only shows a secular increase with ~0.0050 within an interval of ~2 yr. The V–B became bluer suggesting a temperature rise. On the contrary B–L and B–U became redder, suggesting the opposite effect and/or a decrease of the gravity. A precise interpretation is therefore difficult. More observations are needed to study its further behaviour.

Gradually an overwhelming amount of indications are known, see for example de Jager (1980), that the atmosphere and/or photosphere of many high luminous hot stars are continuously subject to unrest and turbulence, some times resulting into an excess mass loss. A few examples follow here.

Spectroscopic studies of early type supergiants revealed radial velocity and line strength variations (e.g. Abt, 1957; Rosendhal, 1970, 1973; Underhill, 1966, 1983a; Sterken, 1977) Indeed Wolf et al. (1974) presume that pronounced time and depth dependent non-thermal photospheric velocity fields exists in supergiants, causing a variation in the absorption lines and photometric variations. Van Paradijs et al. (1976) found radial velocity variations from night to night in the B type supergiant companion of the X-ray binary HD 77581.

A series of puffs resulting from a discontinuous loss of matter, caused a decrease of light output of the hypergiant (hypergiants are stars classified as Ia$^+$) ζ^1 Sco (B1 Ia$^+$) (Burki et al., 1982). Wolf and Sterken (1976) noticed that a decrease in visual light by $0^m.06$ of the star HD 91619 (B5 Ia) coincided with a flare like event in the Hα emission.

Two peculiar depressions in the light of the hypergiant HD 160529 (A2 Ia$^+$) were observed by Sterken (1981) on two nights during a continuous monitoring. Timescales of the events were ~5 min and the depth ~$0^m.1$.

Not only B or later type supergiants show turbulent motions, but also the O type stars, especially the evolved ones (Conti and Ebbets, 1977), with velocities sometimes superceding that of sound (de Jager, 1980). Recent polarization studies have been made of two early type supergiants (09.5 Ia and B1 Ia) and ordered but non-periodic changes were detected (Hayes, 1984). Polarization changes in early-type supergiants were also seen by Hsu and Breger (1982). Probably they are a manifestation of variable mass loss in the extended atmospheres. Hayes suggests that the mass loss may be seated in aperiodic non-radial pulsation.

Andriesse (1979, 1980a, b) explained micro variations of stars with his fluctuation theory of mass loss. This theory predicts cooler spots in the photosphere caused by surges of matter which leave the photosphere stochastically. This theory has been tested on the intrinsic variations of the X-ray binaries HD 153919 and HD 77581 (van Genderen and Windhorst, 1981) adopting that the visual light variations are roughly equal to the bolometric ones. Although the theoretical ratio between the amplitudes of the fluctuations of the O and B type star and the timescales were roughly correct, the theoretical bolometric amplitudes were a few orders of magnitude smaller than the observed ones. The true situation is even worse, since for hot stars the bolometric light variation is in fact larger than the visual light variation. The same is the case for our program stars, although the differences between the size of theoretical and observed amplitudes are much smaller than for the previous cases. It is of course not impossible that part of the smaller micro variations are caused by such a process as described by Andriesse. It is perhaps necessary to revise in his expression for the mass loss rate the dependency on the parameters R, L, and M, since the mass loss rates derived are not quite comparable with the observed ones (Lamers, 1981; Garmany and Conti, 1984).

In any pulsational cycle atmospheric shocks move outwards as has been shown by Burger et al. (1982a, b), de Jager (1981), and de Jager et al. (1984). It is thus conceivable that a part of the small photometric variations are caused by the varying line strengths. Underhill (1984) concluded an account of far ultra violet observations that the small scale variability may be caused by bipolar magnetic regions with associated hotter and cooler spots.

Which of all these different phenomena should be attributed to the $\bar{P}$- or to part of the δ variations or to both is not always clear. Therefore observations made with different techniques should be done simultaneously to investigate this further.

9. Conclusions

We have shown that presumably six out of eight high luminous OB type stars, main sequence stars as well as evolved ones, show a cyclic behaviour of which the periods were found by two period determination techniques. The cyclic behaviour of seventh star, is more uncertain. The periodic behaviour and especially the stability should however be confirmed by further photometry. All periods are much longer, up to a factor of 10 than the theoretical periods for radial pulsations in the fundamental mode. Non-radial pulsations and post-RSG evolution are presumably the reason (Lovey et al., 1984).

The relatively large intrinsic scatter (called δ variations) around the mean light- and colour curves is investigated for periodicity, but apart from HD 105056, there are no such indications. The radial velocity variations of this star obtained by Walborn et al. (1980), were analyzed in the same manner as our photometric observations with two period determination techniques. Both data sets resulted into the same primary and secondary periods. This suggests that some kind of pulsation is the cause of the variation. It is however still a question whether our data for the other O type stars are sufficient to rule out the existence of more periods. The relation between brightness- and colour residuals after assuming a single period is perhaps a sign that no more periods exists (Sect. 6). However this should be confirmed by more observations.

The intrinsic scatter of the average light curves of the orbital revolution of the massive X-ray binaries HD 153919 and HD 77581 are also investigated, but no-periodic character is found either. The photometric behaviour of the cyclic- and δ variations of the O type stars show several differences, tentatively suggesting that they are caused by a mechanism different from the one (likely pulsation) causing the cyclic variations. A possibility is the presence of cooler clouds of moving matter of varying temperature and density expelled by active regions in the photosphere.

The δ variations of the B type stars are likely caused mainly by a difference in the behaviour of each pulsational cycle causing varying periods and light curve shapes. This combined with the same atmospheric and/or photospheric unrest as for the O type stars, but at a larger scale, could be responsible for the more erratic δ colour variations.

The fact that two stars of 40,000 and 50,000 K appear to be variable may suggest that their photospheres are unstable against convection in deeper layers, contrary to theoretical models (Underhill, 1983a), or that they pulsate.

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