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ASTRONOMY AND ASTROPHYSICS

The maximum amplitude of the optical micro-variations of massive O-F type stars (or α Cygni variables, including LBV's or S Dor variables) across the HR diagram ⋆

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Summary. The maximum light amplitude (MLA) of the micro-variations of nearly 100 massive stars with spectral type O 3–F 8 (most of them are super- and hypergiants) are collected from the literature and unpublished material. These variables, called the α Cygni variables, also include the LBV's or S Dor type variables. The S Dor type variables must be in a Quiescent Stage (QS) to detect their intrinsic variations properly.

The log T_{eff}/MLA diagram exhibits a clear separation between S Dor (QS) type variables and the normal α Cygni variables (the majority). Those of the first category show oscillations at least twice as high as those of the second one with the same T_{eff}. Besides the light curves of S Dor type variables are more smooth than for the other blue variables. *These facts suggest that the outer layers of both types of stars where presumably gravity waves occur, differ physically from each other.* For the majority of the normal α Cygni variables the MLA increase from O 3 stars (zero or very small) through B 3 stars ($0^m.1-0^m.15$). For not too massive stars (initial masses $M \lesssim 25\,M_\odot$) the oscillations subside when they become F (and G) type supergiants. For stars with initial masses $M \gtrsim 25\,M_\odot$, the MLA increase to $\sim 0^m.2$ or even larger, if they become A and F type hypergiants. Thus the oscillations vary continuously during the stellar evolution and are a function of mass and luminosity. Between spectral types O 9 and A 0 no stable supergiants seem to exist.

Key words: variable stars – supergiants – photometry – oscillations of stars

1. Introduction

A high precision multi-colour photometric study of a large sample of highly luminous OBA type stars started at the Leiden Observatory in 1981, of which part turned out to be variable. The telescope used is the 90-cm Dutch reflector at the ESO, La Silla, Chile, equipped with the *VBLUW* photometer of Walraven. Part of the results has already been published in a series of papers (van Genderen, 1985 (Paper II), 1986 (Paper V); van Genderen et al., 1985 (Papers I, III, IV), 1988 (Papers VI, VII, VIII)).

According to the nomenclature of the General Catalogue of Variable Stars (Kholopov et al., 1985) luminous variable (ampl. $\sim 0^m.1$) B and A type supergiants are called α Cygni variables after the prototype α Cyg (A2 Ia). This is in accordance with the recommendations of Commission 27 of the IAU at its 12th General Assembly in Hamburg in 1964 and allowing for slight modifications required by the continual growth of information. Since luminous, massive O and F (and later) type stars belong to the same evolutionary sequence as those of type B and A, they also belong to the α Cygni variables. Since only a little number of well monitored massive G and K type supergiants are known, we have omitted them from our analysis. Besides the possible ejection of bright or obscuring shells makes the detection of the intrinsic variations extremely difficult.

It should be emphasized that we only selected stars which are massive: most of them have presumably masses of the order of $M \gtrsim 15\,M_\odot$. Low mass supergiants (Sect. 2) were omitted.

In a number of recent papers and in the review of Lamers (1987) the blue part of the α Cygni variables is called Luminous Blue Variables or LBV's.

In Papers III and VI it is demonstrated that S Dor type stars in a quiescent stage (abbreviated QS) behave in several respects as other variable blue supergiants and therefore should be considered as a small subclass of the α Cygni variables.

From a statistical photometric study of a very large sample of supergiants, Maeder and Rufener (1972) obtained a global idea about the size of the light variations across the top of the HR diagram. In our series of papers the observed maximum range of the light variations, in the present paper called the maximum light amplitude or MLA, is plotted against the temperature (Papers II, V, VII). The reason is that in a not too broad horizontal band at the top of the HR diagram, the T_{eff} can be considered as a relative measure of the evolutionary status, at least if only stars are considered moving into the same direction. A relation emerged between MLA and T_{eff} in the interval 50000–10000 K, in the sense: the lower T_{eff}, the higher MLA. The MLA is very small for O type stars and $\sim 0^m.15$ for A type stars. A similar type of diagram, for 18 LMC supergiants was constructed by Appenzeller (1972) showing the same trend.

In the present paper we shall discuss the log T_{eff}/MLA diagram based on nearly 100 massive O-F type super- and hypergiants selected from the literature and unpublished material.

⋆ Partly based on observations collected at the ESO, La Silla, Chile

2. The definition of the MLA

Subsequent cycles of the light variation of supergiants are always slightly different from each other with respect to length and amplitude. Therefore it is necessary to have observations, distributed over a number of cycles. The more cycles the better. By own experience it is found that the MLA did not increase much any more, if say 30–50 data points are distributed over 5–10 cycles and scattered in time with a base length of about 2–4 yr. However many stars are not studied so intensively. Yet their MLA's based on observations more or less arbitrarily distributed over a number of cycles and within a time interval of a few years, are statistically significant enough for our purpose. This turned out by experiment, when new series of observations of a dozen of them, did not change the original MLA significantly. An increase of 10–30% did occur for half of them.

The MLA can be considered as an objective measure as long as the errors in the data points are always at least an order of magnitude smaller than the total range of the light variation. This is the case indeed.

Variable stars much less frequently observed are important for the statistic, simply because they *are variable*, especially if they were not selected on the basis of suspected variability.

The same is true for stable luminous stars. Then five to ten observations are enough to be pretty sure that they are non variable, provided that the observations were made arbitrarily distributed in say one or two seasons. Thus most of the observational programs, which had the purpose to investigate the stability of luminous stars, also resulted in finding non variable objects. Both categories are therefore used in this paper.

It must be emphasized that the MLA's are in most cases based on the visual light curve. For O and B type stars the colour variations are about an order of magnitude smaller than the light variations (Papers II, V). This is especially the case for the $V-B$ or the equivalent $(B-V)_J$ indices. Consequently, it makes not much difference what kind of band pass is used.

The colour variations increase with respect to the light variations for the A and F type stars. Usually the colour curves are in phase with the light curve and the light amplitudes increase to shorter wave lengths (Paper V). Only one photometric survey, that on FG supergiants by Arellano Ferro (1981), is partly done in blue light only. However since nearly all these stars are non variable during the time of monitoring, no overestimates of the MLA's are introduced.

3. The selection of stars

Since there are different types of variables in the spectral range O to F and often rather luminous, it is necessary to mention explicitely the types which are not used because they are no α Cygni variables. An exception are the six massive variable B[e] stars in the LMC, which we did not use because they are fast rotating stars with peculiar stellar wind phenomena (Zickgraf et al., 1986). Also an exception is the unique object η Car, probably an extreme case of an S Dor type variable, which is surrounded by a bright shell. Photoelectric monitoring from 1963 up to 1986 shows that the visual brightness of the integrated light varied between $V_J = 6.2$ and 5.9. Superimposed on a very long term variability between these limits, smaller light amplitude oscillations occur with a time scale of 1–3 yr, with a total range of $0^{m}.15$ (van Genderen and Thé, 1987). This value, *if intrinsic to the star*, should be considered as a lower limit. This is because of the important contribution of the shell to the total light (visual brightness of the shell is of the same order as for the central star, van Genderen and Thé, 1984), and because of the contribution of a few stars or bright gas clouds within the shell (Weigelt and Ebersberger, 1986; Davidson and Humphreys, 1986). Because of the uncertainty whether the oscillations are intrinsic to the star or not, this MLA cannot be used. An other reason to suspect its direct relation to the oscillations of the star is the very long time scale as compared to those of the other S Dor type stars. We tentatively adopt for the primary object $M_{\rm bol} = -11.1$ (Davidson and Humphreys, 1986), and used in Fig. 2 with a question mark, although η Car is not plotted in Fig. 1.

Further we omitted five distorted massive stars in close binary systems. They fill, or nearly fill, their Roche lobes, among them three massive components in X-ray binaries. The MLA of their intrinsic variations turn out to be somewhat larger than for non distorted stars (Papers II, VII, and VIII). Also not used is the MLA of HD 57061 (O 9 I) (Papers I and II), which is a member of a multiple binary (Hoffleit, 1982).

No α Cygni variables are:

1. The Be stars (less luminous than the B[e] stars). Their variability is very complicated and part of the light variations is caused by changes in or by the circumstellar envelope and disk (e.g. Underhill, 1966; Slettebak, 1979; Harmanec, 1983).

2. The early B type stars named β Cephei stars. They belong to various luminosity classes (I–V) and pulsate regularly in the non radial p-modes. Periods and amplitudes of the light curves are stable, suggesting that the instability mechanism lies deeper in the stellar interior than for the α Cygni variables. A review is given by Lesh and Aizenman (1978).

3. The low mass 53 Per stars, of spectral type B 3–7 (III–V). They pulsate not quite regularly, perhaps caused by multiperiodicity. Their light amplitudes are thus not stable. Presumably these stars pulsate in the non radial g-mode (e.g. Waelkens and Rufener, 1985).

4. The low mass B type super- and hypergiants like HR 4049 (Lamers et al., 1986) and HD 213985 (Waelkens et al., 1987). Presumably they are post AGB proto planetary nebulae stars.

5. The low mass F type supergiants at high galactic latitudes named UU Her type stars. Presumably they are post AGB proto planetary nebulae stars also, e.g. Sasselov, 1985; Sasselov et al., 1987).

4. Description of the sample

The sample used for the log $T_{\rm eff}$/MLA diagram consists out of nearly 100 selected young massive stars from the Galaxy and the LMC. The spectral types are O 3 up to F 8. Most of them have masses $M \gtrsim 15\,M_\odot$. A few F type supergiants have presumably masses of $\sim 10\,M_\odot$. The luminosity classes are mainly I and V. Only a few stars are classified as II or III.

Table 1 lists the stars, their spectral types and MLA value in log intensity scale. In order to use a uniform temperature scale we applied the spectral type/$T_{\rm eff}$ table of de Jager and Nieuwenhuyzen (1987).

A few special cases should be mentioned here:

1. Most of the O type stars have the spectral characteristic "f", which indicates that at least the He II 4686 and generally N II 4634, 4640 are in emission.

2. Three stars have a strong nitrogen contribution in the spectrum. It is suggested that blue stars, which were in the red supergiant phase have already altered their surface chemical

Table 1

SP	HD/BD/CD Name	MLA (log int)	Ref.
O 3 V	93205	0.009	1, 2
O 3.0 V (f)	303308	0	9
O 4.0 (V) f	164794	0	9
O 5.0 V f	46223	0.008	4, 5
O 5.5 VN (f)	76556	0.007	1, 2
O 6.0 V f	91572	0	4, 5
O 6 III (f)	93130	0.009	9
O 6.0 (V) f	172175	0.011	9
O 6.5V (f)	91572	0	9
O 6.5 f	148937	0	9
O 6.5 III (N) (f)	175876	0.006	9
O 7.0 V p	37022	0	9
O 7.5 V f	46573	0	9
O 8.0 I af	151804	0.020	4, 5
O 8 Ib (f)	120521	0.018	4, 5
O 8.5 Ib (f)	74194	0.016	4, 5
O 9.0 V	37041	0	1, 2, 5
O 9 II	305523	0.006	1, 2
O 9.5 III	47432	0.033	9
O Iafpe	R 84	0.08	19
	R 85	0.16	19
O Bf: pe	R 99	0.12	19
B 0 Iae	R 78	0.08	19
B 0 Ia	167264	0.020	22
B 0 Ia	HR Car	0.040	25
B 0 Ia	AG Car	0.070	6
B 1 Ia$^+$	P Cyg	0.080	13, 14
B 1 Ia	169454	0.036	22
B 1 Iab	96248	0.035	1, 2
B 1.5 Iae	190603	0.032	17
B 1.5 Ia	BD − 14°5037	0.046	22
B 1/2 Ia$^+$	152236	0.052	10
B 1/2 IaN	157038	0.038	9
B 2 Iae$^+$	80077	0.03	21
B 2 Iab	148379	0.044	4, 5
B 2 Ib	206165	0.024	17
B 2 Ia	14956	0.025	18
B 2 Ia	99953	0.036	22
B 2.5 Iab	R 71	0.090	3, 4
B 2.5 eqIa	R 81	0.028	20
B 3I a	75149	0.023	9
B 3 Iae	198478	0.024	17
B 3/5 Iab	62150	0.048	1, 2
B 5 Ia	91619	0.038	22
B 5/7 Ia/ab	102997	0.033	4, 5
B 6 Ia	15497	0.023	18
B 6 Ia	80558	0.032	9

Table 1 (continued)

SP	HD/BD/CD Name	MLA (log int)	Ref.
B 6 Iab/b	74371	0.020	9
B 8 Ia	168625	0.048	22
B 8 Ib	208501	0.028	17
B 9 Ia	96919	0.044	22
B 9 Ia$^+$	168607	0.054	22
B 9 Ieq	R 55	0.11	19
B 9: Ieq	R 110	0.13	19
BIe	R 74	0.10	19
A 0 Ia	92207	0.028	22
A 0 Ib	46300	0	9
A 1 Ia	12953	0.026	18
A 2 Ia$^+$	CD − 33°12119	0.080	12
A 2 Ia$^+$	160529	0.068	23
A 2 Ia	14489	0.020	17, 18
A 2 Ia	100262	0.032	22
A 2/3 Ia	92693	0.032	4, 5
A 3 Ia$^+$	33579	0.060	11
A 5 Ia	17378	0.015	18
A 5 Ia/ab	81471	0.009	9
A 5 Ib	59612	0	9
A 5 Ib	68601	0	9
A 7 I	269604	0.07	19
F 0 Ia	90772	0.032	26
F 0 Ia	269612	0.06	25
F 0 Iab/b	57118	0	26
F 0 Ib	80404	0.012	24
F 0 I	135153	0	26
F 0 Ib	90853	0	24, 26
F 0 Ib	159532	0	26
F 0 I	168393	0	26
F 0 II	61227	0	26
F 2 Ia$^+$	74180	0.06	21
F 2 Ia	161471	0	26
F 2 Iab	75276	0	26
F 2 Ib	70761	0	26
F 2 II	57321	0	26
F 5 Ia	17971	0.015	18
F 5 Iab	115400	0	26
F 5 Ib	182900	0	26
F 5 II	164584	0	26
F 6 Ib	180028	0	26
F 8 Ia$^+$	R 92	0.12	15, 16
F 8 Iab	146143	0	26
F 8 Iab	151097	0	26
F 8 II	57623	0	26
F 8 II	65228	0	26
F 9 Ib	133683	0	26

References for Table 1

1–6	Papers I–VI, respectively
9	Paper IX (in preparation)
10	Burki et al. (1982)
11	van Genderen (1979)
12	van Genderen et al. (1983)
13	van Gent and Lamers (1986)
14	Percy et al. (1988)
15	Grieve et al. (1985)
16	Eggen (1983)
17	Percy and Welch (1983)
18	Rufener et al. (1978)
19	Stahl et al. (1984)
20	Stahl et al. (1987)
21	Steemers and van Genderen (1986)
22	Sterken (1977)
23	Sterken (1981)
24	van der Wal and van Genderen (1988)
25	van Genderen et al. (in preparation)
26	Arellano Ferro (1981)

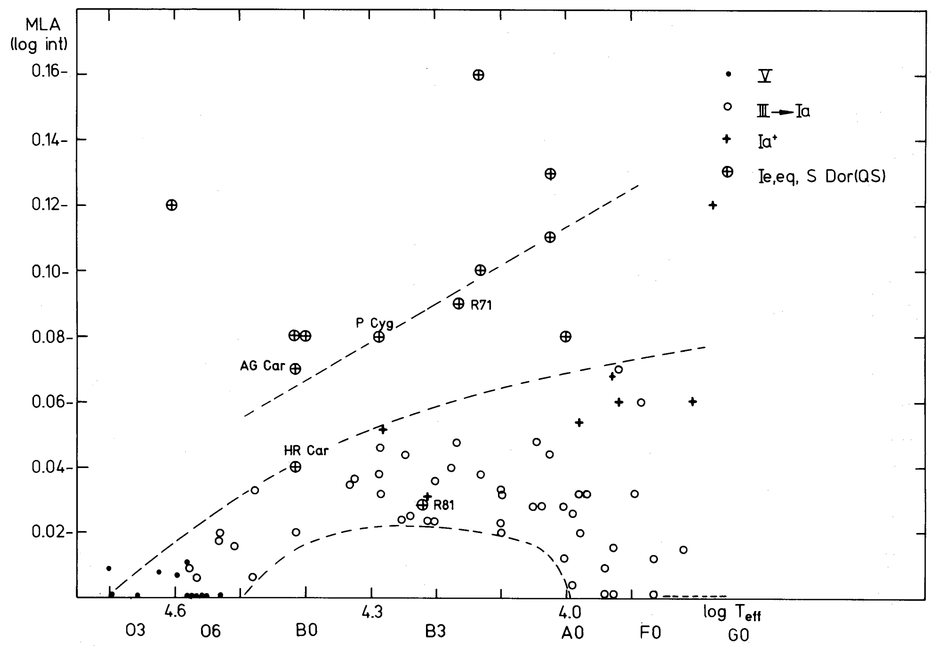

Fig. 1. The maximum light amplitude (MLA, in log intensity scale) of the micro variations of nearly 100 massive stars in Galaxy and LMC as a function of log T_{eff} (and spectral type)

composition by exposing products of the CNO cycle at the surface like HD 157038 (B 1/2 IaN) e.g. Lennon and Dufton (1986). Extensive *VBLUW* photometry of this object is analyzed, but not yet published.

It is suggested that extra mixing can be caused by rapid rotators, such as for the blue stragglers e.g. Schild and Berthet (1986). One star in our sample (Paper II) could be a blue straggler: HD 76556 (O 6/5.5 VN (f)), which is not listed by them.

3. Four objects belong to the subgroup of S Dor type variables. Their microvariations were detected while they were in a quiescent stage (abbreviated QS): P Cyg, R 71, AG Car, and HR Car. Three stars are *suspected* as being S Dor (QS) type stars, also called Ofpe/WN9 objects: R 84, R 85 and R 99 in the LMC (Stahl et al., 1984). The evolutionary stage of S Dor variables is presumably intermediate between blue supergiants and the Wolf-Rayet stars (Stahl et al., 1984).

4. Five stars are according to their spectral characteristics classified as P Cygni Type stars (PCT, see Lamers, 1986) of which four are also S Dor variables, (see 3.) and R 81.

5. The log T_{eff}/MLA and the HR diagrams

Figure 1 shows the log T_{eff}/MLA diagram for the nearly 100 selected massive luminous stars listed in Table 1. The meaning of the different symbols is explained in the diagram. The difference between Ia$^+$, Ie, Ieq (emission lines with P Cygni profiles) and S Dor (QS) type stars is vague. They all have overlapping spectroscopic characteristics.

Figure 2 shows the theoretical HR diagram for most of the variables plotted in Fig. 1. The distance are taken from the quoted references or from Humphreys (1978). Variables with unknown distances are not plotted. For the LMC objects a distance modulus of 18.6 is used and the reddenings quoted in the papers from which we used the data. If no reddening was given, then only a fore ground extinction was applied of $0\overset{m}{.}2$.

The diagram shows three evolutionary tracks for initial masses of 15, 25, and 60 $M_\odot$ (Maeder and Meynet, 1987), the Humphreys-Davidson limit (Humphreys, 1987, a few $\bar{P}$ = const. lines for variable supergiants (Maeder, 1980), and the Cepheid strip for LMC Cepheids with a few P = const lines (van Genderen et al., 1986). The numbers indicate the length of P in days. Symbols are the same as in Fig. 1.

6. Discussion

The region in which most of the normal α Cygni variables occur, is roughly outlined by the curved dotted area in Fig. 1. The area for the about 20 practically stable F type supergiants of Arellano Ferro (1981) is indicated by a straight dotted line along the

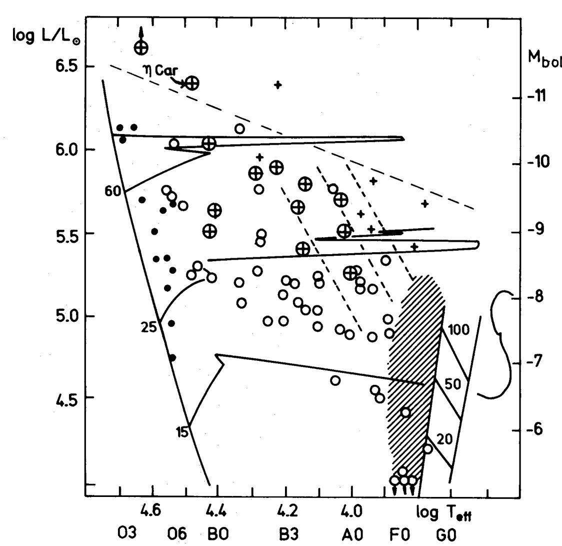

Fig. 2. The theoretical HR diagram for the stars of Fig. 1, at least if the distance is known. Symbols have the same meaning as in Fig. 1. The Cepheid instability strip for LMC supergiants is sketched at the right bottom corner with a few P = const lines (van Genderen et al., 1986)

horizontal axis. (Many of his G type supergiants also appear rather stable). The fact that most of the F and G type supergiants tend to be more stable than their blue counterparts is substantiated by the photometric study of van Genderen et al. (1986) of roughly 100 FG supergiants [most of them are situated just at the left of the Cepheid instability strip sketched in Fig. 2 (hatched area)]. These stars were observed three to seven times in a time interval of three months, yet only a very small number showed evidence of a light variation. Thus if some of them would appear to be variable yet after a careful photometric study, then their MLA's will be likely very small, say $\lesssim 0.02$.

Four A and F type hypergiants (HD 33579, HD 74180, HD 160529, and HD 168607) and two luminous LMC objects (circles) (HDE 269604 and HDE 269612, the latter one based on unpublished *VBLUW* photometry), form a group with high amplitudes. A glance on Fig. 2 shows that these ones are all *much more massive* than the AF supergiants with low amplitudes and the 100 FG type supergiants just referred to (hatched area in Fig. 2). Thus the widening between the two dotted lines *is caused by a difference in mass and luminosity*.

It is of interest to notice that the O stars with a strong stellar wind (Of), and which are slightly evolved (Feinstein et al., 1986), are not more instable than one should expect if the increasing instability is a measure for the evolutionary status, and the evolution runs along the sequence OV – Of – BI – AI etc. This is in agreement with Maeder's (1983) scenario for the models with an initial mass of $M \lesssim 60\,M_\odot$. Indeed most of our stars should have masses below this limit in view of their distribution in Fig. 2. Therefore we can interpret the trend of the MLA as an *evolutionary effect*, which for not too large masses, reaches a maximum at spectral type $\sim$B5. The oscillations *practically disappears* for stars with initial masses $M < 25\,M_\odot$ by the time they become of spectral types FG, which is just at the blue side of the Cepheid instability strip.

For the more massive (initial masses $M > 25\,M_\odot$) and more luminous stars, the oscillations increase further in strength. It is possible that their larger instability is caused by the increasing dissipation of turbulent energy as suggested by de Jager (1984), which may become effective now, because of the very low effective surface gravity.

Although at a luminosity of a $\sim 40\,M_\odot$ model, the gravity decreases by a factor of 100 from $\log g \sim 3$ at $\log T_{\rm eff} \sim 4.5$ to $\log g \sim 1$ at $\log T_{\rm eff} \sim 4.0$, the MLA increases only by a factor 3–4. At present it is not possible to translate the strength of a light variation into a parameter which characterizes the strength of the oscillations in the stellar photosphere.

Below the lower enveloping dotted line there is a remarkably empty space. Apparently no or at most a very little number of stable supergiants exists in the spectral range O 9–A 0. This gap must be real, since many of the consulted surveys were done without a selection on suspected variability.

Clearly separated from these normal α Cygni variables, lie the S Dor (QS) type stars and those which are suspected as such, like R 84, R 85, R 99 (Sect. 3), and a few other supergiants in the LMC with emission lines (e) and P Cygni profiles (eq) in the spectrum. (The exceptions HR Car and R 81, will be discussed below.) The dotted line roughly indicates their location. Further, careful monitoring of specimen like R 99 and R 85, should find out how real the large light amplitudes are and how much of it is intrinsic. After all the large amplitude for R 81 appeared to be largely caused by an eclipse phenomenon (Stahl et al., 1987), see further.

The separation of the two groups of α Cygni variables in Fig. 1, does not suggest an evolutionary sequence between the OV type phase and the S Dor type phase. A short lifetime in the transistion stage, in which very massive stars (60–120 $M_\odot$) lose most of their mass (Lamers and Fitzpatrick, 1988) and the fact that so far a little number of Of stars and supergiants with $M > 60\,M_\odot$ and $M_{\rm bol} < -10$ were photometrically monitored could be the causes.

The fact that the light oscillations are at least a factor of two stronger than for the normal variables with the same temperature, indicates that the possible gravity waves in their outer layers are stronger. There is an other obvious difference between the two types of light oscillation. That is the fact that the variations of S Dor type stars are *smooth*, while those of the normal B type α Cygni variables often show more humps and bumps. Compare the light curves of R 71, AG Car, and HR Car (Papers III, VI and a paper in preparation, respectively) with those of stars discussed in the other papers of this series. The conditions for more chaotic small scale turbulence are obviously unfavourable near the surfaces of the S Dor type stars. *Thus there is a marked physical difference between the outer layers of S Dor (QS) variables and the other blue super- and hypergiants*. Perhaps this is not surprising, considering the supposed evolutionary status of these stars as blue supergiants on their way to become WN9 stars. The spectra of the S Dor (QS) stars R 84, R 85, and R 99 are classified as Ofpe/WN9 (Stahl et al., 1984). The same is the case for AG Car (QS) (Stahl, 1986). They also differ from normal α Cygni variables by their higher mass loss rate by a factor 3–10, even if they are in a quiescent stage (e.g. Stahl et al., 1983; Lamers and Fitzpatrick, 1988).

It must be noted that if the variations are caused by a rotating spotted star as suggested for some supergiants (Underhill, 1984; Harmanec, 1987), then the conclusion above on the physical difference between the two types of variable stars stays the same. However there are two facts which slightly favours the oscillation mechanism rather than the spotted model. Firstly this is the widening in Fig. 1 of the curved area near spectral type F, caused by the extreme low surface gravity for the hypergiants. This makes it more easy for gravity waves and large scale turbulence to become stronger. Secondly, the fact that the $\bar{P}$ = const lines of the α Cyg variables lie practically in the extension of the P = const lines of the Cepheids (see Fig. 2), also points into the direction of a pulsation phenomenon.

Two stars with similar spectroscopic characteristics, R 81 and HR Car, remain to be discussed. R 81 is spectroscopically similar to P Cyg and called the "P Cyg of the LMC" by Wolf et al. (1981). Its large light amplitude appeared to be due to a periodic eclipse phenomenon by a wide binary (Stahl et al., 1987). However its intrinsic oscillations behave unlike that of the other S Dor (QS) type stars in view of the small range of the micro-variations. The number of observations is large and made in five subsequent seasons, thus the MLA plotted in Fig. 1 is reliable.

HR Car (B 0 Ia) is a genuine S Dor (type variable (e.g. Viotti, 1971). Monitoring has just started. So far a few cycles ($\bar{P} = 20^{\rm d}$) were covered, but the MLA is still too low compared to the other S Dor (QS) variables. However, the star is not completely in a quiescent stage yet in view of the present magnitude: $V_J \sim 8.2$, while in the minimum $V_J \sim 8.7$. Thus the brightness of the envelope could have surpressed the observed range in the micro-variations. Further monitoring is clearly required.

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