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New discoveries on the S Dor phenomenon based on an investigation of the photometric history of the variables AG Car, S Dor and Eta Car

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Abstract. A century of photometric observations of AG Car and S Dor is investigated for general characteristics and possible periodicities in the occurrence of the S Dor (SD) phases, defined as episodes of a radius and an apparent brightness variation at a more or less constant luminosity. We identified two types of such phases: the "very-long-term" (VLT) and the "normal" SD phases. The latter are superimposed on the first.

The time scales for the VLT-SD phases are in the order of decades for both variables. The normal SD phases of AG Car and presumably also of S Dor obey stable periods of $371^{\rm d}4 \pm 0^{\rm d}6$ and 6.8 ± 0.1 yr, respectively. We suspect that the SD-, or LBV phenomenon is provoked by two types of pulsational modes.

The oscillating O-C values for both variables indicate the possible presence of beat cycles. Their time scales are of the order of years to decades.

We found, at least for the SD activity of AG Car, further support for a radius change of the star and a more or less horizontal displacement in the theoretical HR-diagram. However, S Dor has a higher luminosity in minimum than in maximum, amounting to $0^{\rm m}5$–$1^{\rm m}$ depending on the range in the visual magnitude ($1^{\rm m}$–$2^{\rm m}4$).

Inconsistencies between existing temperature scales during the light variations of AG Car were noticed.

We found no cyclic pattern whatsoever in the SD phases of Eta Car. The time scale for such events within the last 20 yr lies between 1 and 3 yr. There is evidence that over the last 20 yrs the central LBV in the Eta Car system experienced a rising branch of a VLT-SD phase, which appears to furnish, according to the secular colour change, indirect support for an ongoing decrease of the circumstellar dust density.

Key words: technique: photometric – stars: individual AG Car, S Dor, Eta Car – stars: variables – stars: supergiants – stars: oscillations

1. Introduction

Since the early 1980's there exists some suspicion that during the S Doradus-type variability of LBVs (during dimming the colour becomes bluer and during brightening red), the radius could be variable (van Genderen 1982). It was also known for some time, that the excursion in the HR-diagram happens more or less at constant $M_{\rm bol}$ according to van Genderen (1979) and Wolf et al. (1981), later confirmed by others. Indeed, according to Leitherer et al. (1989), de Koter (1993) and de Koter et al. (1996), the radius of an LBV increases considerably during its visual brightness increase. According to de Koter et al. (1996), the change of the photospheric radius and temperature cannot be due to the formation of a pseudo-photosphere in the wind induced by a dramatic increase in mass-loss rate. It is rather induced by the combined effect of an increase of stellar radius and a reduced effective gravity. A mass loss increase occurs, but not always, e.g. de Koter et al. (1996).

Contrary to our previous papers on this subject, we shall call such an active state an "S Dor phase", or abbreviated "SD phase", instead of an "SD eruption". According to the studies mentioned above and the present one, the SD phase can be characterized as a slow pulsation during which the star moves more or less horizontally to and fro in the HR-diagram. The mass-loss rate is generally higher than for normal super- and hypergiants.

Like Lamers (1987) we propose that the designation "eruption" should be confined exclusively to events like the one observed in Eta Car around 1843 (magnitude rise by more than $3^{\rm m}$), characterized by a dramatic mass-loss event. Humphreys

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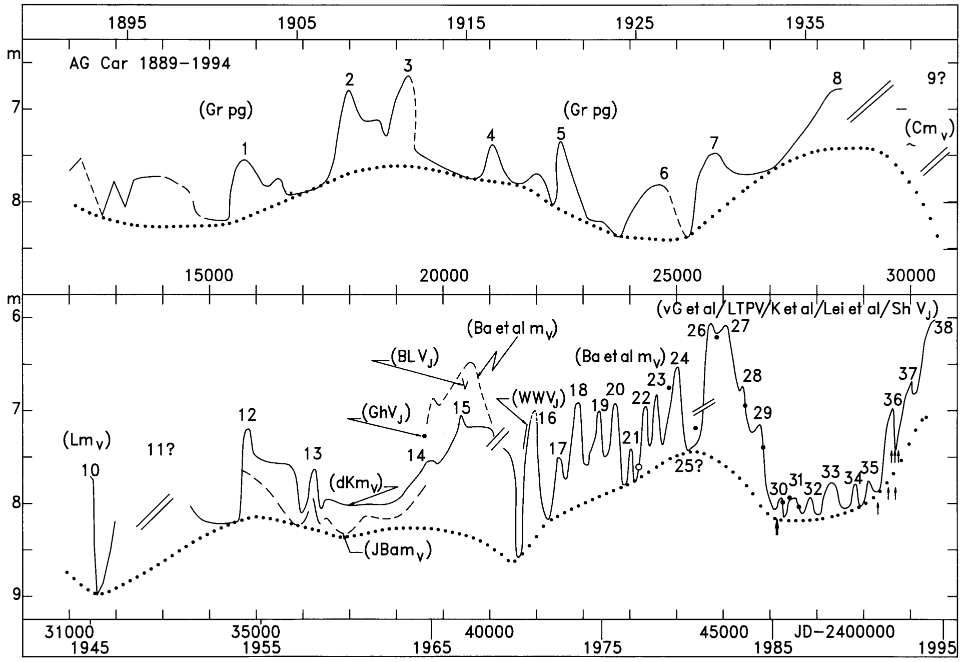

Fig. 1. The light curve of AG Car 1889–1994. See the text for further explanation

& Davidson (1994) often use the term "eruption" to describe the apparently irregular behaviour, because in many ways LBVs remind us of geysers (see also Maeder 1992) or volcanoes. For a complete review of the SD-, or LBV phenomenon until 1993, the reader is referred to Humphreys & Davidson (1994).

In the present paper we investigate the frequency of occurrence of SD phases for AG Car and S Dor based on a century of observations and look for possible periodicities and general characteristics. The ranges of temperature during the light variation of AG Car based on various studies are compared with each other. An attempt has been made to compare the observed ranges in the apparent magnitudes with those expected for a radius change during horizontal evolution in the theoretical HR-diagram. Any deviation should then be attributed to a marked influence of the physical changes of the extended atmosphere and/or to a non-horizontal evolution.

Finally we investigate the frequency of SD phases of Eta Car, based on 167 yr of photometric observations.

2. The light curve of AG Car 1889–1994

Figure 1 shows the schematic light curve of AG Car = HD 94910 comprising the time interval 1889–1994 based on the following sources:

1) The photographic light curve 1889–1936 of Greenstein (1938) in the figure marked with: (Gr pg).

2) The visual light curve of Mayall (1969) covering the years 1940–1969 based on the observations of three observers: A.W.J. Cousins (Durban), H. Luft (Sao Paulo) and R.P. de Kock (Cape), in the figure marked with: (C m_v), (L m_v) and (dK m_v), respectively.

3) One V observation by Graham (1968) made in the VBLUW system of Walraven in 1964 and transformed into the V_J of the UBV system ($V_J = 7.29$) marked with: (Gh V_J). Further, two short photoelectric runs in the V_J passband by Bond & Landolt (1970) made in 1967 and by Wisse & Wisse (1971) made in 1970, marked with: (BL V_J) and (WW V_J), respectively.

4) The visual observations by the Variable Star Section of New Zealand collected by Bateson (1993) covering the years 1954–1994, of which we used three portions:

a. Those between 1954 and 1964 observed by two observers A.F. Jones and F.M. Bateson, showing a relative small scatter and mutually very consistent magnitude estimates. They are represented by a dashed curve between JD 34700 (for the sake of clarity we omit the first two digits 24) and JD 38700 and marked by (JBa m_v). They are systematically fainter by 0^m2–0^m3 than the results of (dK m_v). The former shows more structure, but the general characteristics of both are more or less similar.

b. Those between 1965 and 1969, observed by many more observers, experienced ones as well as beginners. Understandably in this case the scatter is larger, $\pm 0^m5$, sometimes more. The smoothed results are depicted by the dashed curve between JD 38750 and JD 40250 and marked with (Ba et al m_v). During this period the systematic difference with (dK m_v) is of opposite sign and there is a close correspondence with the photoelectric observations (BL V_J). The size of the sudden jump between sets a. and b. is certainly not real and must be attributed to inconsistencies between the results of the observers mentioned in point a. and the average of the much larger group of observers in point b. In this respect the curve (dK m_v) is much more uniform.

c. Those between 1969 and 1980 represented by a full curve and marked with (Ba et al m_v). This part is also shown by Hutsemékers and Kohoutek (1988).

After 1980 (∼ JD 44060) we exclusively use the photoelectric observations, but since they are not numerous during the high maximum of JD 45000 we consulted the visual light curve for the epochs of the extrema.

5) The photoelectric observations in various photometric systems made between 1980 and 1990. These observations are based on work by van Genderen et al. (1988, 1990), the observers of the Long-Term Photometry of Variables (LTPV) group organized by Sterken (1983) and published by Manfroid et al. (1991) and Sterken et al. (1993), and the observations by Kilkenny et al. (1985). For a first discussion of most of these data we refer to Spoon et al. (1994).

6) Further observations by the LTPV group between 1991 and 1994 and published by Manfroid et al. (1994) and Sterken et al. (1995), unpublished V observations (VBLUW system) made in 1989 and 1990, V_J observations by Leitherer et al. (1994) and V_J observations by Shore (priv. comm. to Schulte-Ladbeck et al. 1994). The portion of the light curve based on the observations described in points 5) and 6) are marked with: (vG et al./LTPV/K et al./Lei et al./Sh V_J).

An attempt has been made to transform the photographic part of the light curve to the magnitude scale of V_J or m_v. Since the colour $(B-V)_J$ of AG Car amounts to ~ 0.5, the photographic part has been brightened by roughly the same amount, assuming that blue sensitive plates were used.

It appears that the V_J observations (Gh V_J) and (BL V_J) of point 2) are $\sim 0^m3$ brighter than the (dK m_v) observations also of point 2). Thus, presumably, the light curve of the latter should be adjusted by that amount to be comparable with the V_J scale. On the contrary, the light curve (Ba m_v) appears to be closer to the V_J scale considering the close match with (WW V_J) and three scattered V_J observations listed by Lamers et al. (1989) (black dots in Fig. 1; we return to these observations later).

The light curve in Fig. 1, representing the continuously varying SD activity of AG Car, has been obtained by drawing a smooth curve through the various sets of data points. For the photographic and visual parts before JD 40000, we omitted features lasting shorter than $\sim 100^d$ and with amplitudes $< 0^m4$. In view of the scatter in the individual observations it is not justified to consider these as real features. Also the micro variations of the LBV in the more accurate recent parts were ignored (although they are real, and presumably caused by pulsations). These micro variations, generally present during the faint phases, have an amplitude of $\sim 0^m1$ and a quasi-period of $\sim 13^d$ (van Genderen et al. 1988, 1990). The colour curves of these micro variations in the phase diagrams are generally blue in the maxima and red in the minima of the light curve, similar to the micro variations of variable super- and hypergiants (non-LBVs). Therefore, we name them from now on "α Cyg-type variations". Thus, their average behaviour is opposite to the colour behaviour of SD phases. Poorly covered parts of the light curve in Fig. 1 were dashed. The meaning of the various symbols (circle, black dots and arrows) will be explained in Sect. 5.

Table 1. Details of the maxima of AG Car; see the text for definitions

No.	Max JD-2400000	E	Ampl. (m)	Total duration (d)	Duration r. branch (d)
1	15700	−69	0.8	(600)	(100)
2	18050	−63	1		(340)
3	19200	−60	0.7	(600)	(390)
4	21070	−55	0.5	(300)	(150)
5	22600	−51	0.8	(650)	(200)
6	(24680)	−45	(0.5)	(1500)	(700)
7	25730	−42	0.9		(400)
8	28320	−35	1.2		(340)
9	?				
10	31520	−27	1.3		
11	?				
12	34850	−18	1.1		
13	36230	−14	0.5	(350)	(150)
(14)	(38850)	−7	(0.5)		(850)
15	39400	−5	(0.5)	(1100)	(450)
16	(40900	−1	(1.6)	(600)	(250)
17	41500	0	0.8		240
18	41820	1	0.8	450	210
19	42260	2	0.6	380	180
20	42640	3	0.8	450	200
21	42980	4	0.4	200	60
22	43300	5	0.8	280	200
23	43550	6	0.5	300	120
24	44000	7	0.85	550	280
25?		8			
26	44720	9	1.4		
27	45030	10			
28	45410	11			
29	45800	12			
30	46200	13	0.2	220	
31	46540	14	0.3	330	
32	46830	15	0.3	350	
33	47300	16	0.4	600	
34	47820	17	0.25	350	
35	48170	18	0.3	230	130
36	48600	19	0.9	450	330
37	49040	20	0.9	400	320
38	(49400)	21	0.85		(280)

3. Investigation of the cyclic behaviour of SD phases of AG Car

According to presently held general opinion (Sect. 1), any brightness difference with respect to the minimum brightness (which is about $V_J = 8.2$ in the photoelectric light curve of AG Car), should be caused mainly by the increase of the stellar radius of the LBV. To investigate the various time scales, we started with the very-long-term (VLT) behaviour of the brightness. In Fig. 1 we sketched a smooth curve through the minima by ignoring, as a first approximation, features shorter than $\sim 3000^d$. The result is represented by the thinly dotted curve. This curve should then be considered as the very long-term SD (VLT-SD) phase of AG Car. The time scale for this state lies between 7000^d (19 yr) and 10000^d (27 yr) and has an amplitude of $\sim 1^m$. No significant secular trend in the average brightness is present.

Superimposed on this trend occur numerous "normal" SD phases of a shorter duration. We assigned to each maximum a number which runs from 1–38. For the photographic part of the light curve we only numbered those having an amplitude $\geq 0^m4$ with respect to one of the adjacent minima. Due to the many time gaps (up to a few hundred days) and the scatter in mainly the photographic magnitudes amounting to $\pm 0^m3$ (this is sometimes also the case for the visual magnitudes), smaller light curve features were smoothed away.

The better defined light curve after JD 40000 contains the maxima 16–38. It shows a wealth of prominent SD phases with a relative small time scale ($\sim$ 1 yr) and SD phases with amplitudes as small as 0^m2 (maxima 30–35) and roughly the same time scale (see further). To outline the light curve for those extrema that are not well covered by photoelectric data, we consulted the visual light curve of Bateson (1993). For example, maxima 26, 27 and 28 are based on the visual light curve. (The relative reliability of the modern visual observations can be illustrated by the fact that all observed photoelectric extrema are also present in the visual light curve). In this way we are pretty sure that we have found a complete sequence of maxima, definitely from 17–38 (for the reliability of maximum 16 see below).

The precise counting of the early maxima is hampered, not only by the smoothing of the scatter through which we could have missed a lot of small maxima, but also by a few large time gaps. It may be, but there is unsufficient proof that around JD 30000 a prominent maximum was present (no. 9?) as well as around JD 33000 (no. 11?). It should be stressed that the prominent early maxima likely consist out of a number of shorter time scale maxima like the more recent ones (as will become clear from the period analysis below).

Table 1 lists the epochs of the maxima, the cycle count E (see further), the amplitude, the total duration of the SD phase, the duration of the rising branch, all estimated with the aid of the original light curves. Uncertain values are bracketed or left open. Definitions are as follows: the amplitude is the range between maximum and the preceding minimum, the total duration of the SD phase is the time difference between the preceding and following minimum, the duration of the rising branch is the time span from the preceding minimum to the following maximum.

The first part of Table 1 lists the early prominent maxima 1–15 for which the amplitude is $\geq 0^m4$. The estimated uncertainty in these epochs varies between $\pm 50^d$ and $\pm 150^d$. Bracketed values are uncertain because of the peculiarity of one of the extrema.

The average time scale for these prominent SD phases with light amplitudes $\geq 0^m4$, and assuming that two possible prominent maxima were missed in the gaps (9? and 11?), amounted to 5 ± 2 yr within a time interval of 65 yr (JD 15000–JD 40000). In a previous attempt to estimate the timescale for the major SD phases in the past 5.5 ± 1.8 yr was suggested (van Genderen et al. 1988).

The second part of Table 1 lists the more recent maxima 16–38. Maximum 16 is not well covered near the maximum brightness and could well consist of two separate SD phases. Therefore it has been bracketed in Table 1. Also, maximum 38 has been bracketed because the continuation is not known yet. The presence of maximum 25 is suggested by the period analysis given below (the time difference between the maxima 24 and 26 is twice the average time difference between the maxima 17–24 and 26–38, but from the visual light curve alone we cannot give a decisive answer. Perhaps there is a sign of a weak maximum. The uncertainty in the epochs of maxima 17–35 amounts to $\pm 25^d$.

The high maxima 26–27 and 38 (12.9 yr apart), are the brightest (near $V_J \sim 6$) of the century (taking into account the necessary adjustment of the photographic magnitude scale). The time difference with respect to one of the deep adjacent minima (depth $\sim 2^m$) is relatively short due to the contribution of the VLT-SD cycle to the brightness variation.

Table 1 and Fig. 1 give 13 contiguous cycles which leave no doubt concerning the numbering of cycles in the time interval 44720–49400, the maxima 26–38, containing the small amplitude sequence 30–35 (0^m2–0^m5). A least-squares solution yields P = $395^d6 \pm 1^d3$. Equally, 8 contiguous cycles are seen in the preceding time interval 41500–44000, the maxima 17–24, with mainly moderate amplitudes (0^m5–1^m). A least squares solution leads to P = $352^d5 \pm 4^d7$. Though these solutions point to a significant change in the value of the period, the difference is not large enough to introduce any doubt concerning the count of cycles in the whole time interval spanning both groups of times of maxima. Evidently, one maximum, number 25, must be added between JD 44000 and JD 44720 (see further).

As mentioned above, the maxima 30–35 have very small amplitudes (0^m2–0^m5) and occur at a 0^m5 lower brightness level than all other maxima. That they also represent SD phases has been demonstrated by the reddening of the colour indices during the rise to the maxima and the blueing during the decline to the minima (van Genderen et al. 1990). Thus, they should not be called "α Cyg variations" (Sect. 2), a term to be reserved exclusively for naming the pulsations with a quasi-period of the order of 13^d superimposed on these SD phases.

The complete set of 22 maxima (17–38) yields the least squares ephemeris:

$$\begin{aligned} \mathrm{JD}_{max} = \; & 41415.3 \; + 373^d0 E \\ & \pm 43.1 \quad \pm 1^d8 \quad m.e. \end{aligned}$$

This formula, in turn, allows assigning a unique E value to all preceding times of maximum (listed in Table 1), and the complete set of 35 observed times of maximum leads to the final ephemeris:

$$\begin{aligned} \mathrm{JD}_{max} = \; & 41426.2 \; + 371^d4 E \\ & \pm 17.8 \quad \pm 0^d6 \quad m.e. \end{aligned}$$

which indicates that the 371^d4 period can be considered as a stable one over nearly a century! Thus, most of the so called "major maxima" (before maximum 16) consist of a number of

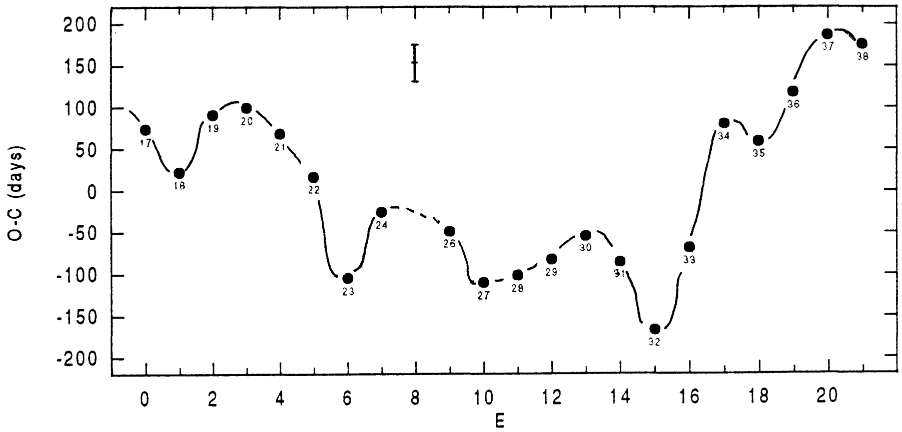

Fig. 2. The O-C diagram for the successive cycles 0–21 representing the observed maxima 17–38, for AG Car, applying a period of 371^{d}4. The long-term wave in the O-C values has a time scale of 21.6 yr. The error bar amounts to twice $\pm 25^d$

smaller time scale SD phases. Most of our epochs of maximum light should concern the most prominent one of the sample. Further, considering the $\pm 0^m 3$ scatter in the photographic and visual observations and time gaps, a lot of small amplitude SD phases, of the type of maxima 30–35, were missed. The mean errors of the ephemeris are mainly caused by the errors in the JD_{max}, the missing maxima are of less influence on the accuracy of the solution.

Figure 2 shows the O-C diagram for the successive cycles E = 0–21, where the data points are marked with the number of the maximum from 17 to 38 and connected by a smooth curve. A long-term trend wave is suggested of $\sim 7900^d$ (21.6 yr) with an estimated accuracy of 10%, with an amplitude much larger than the estimated error of $\pm 25^d$, see the error bar. Figure 3 illustrates the complete O-C diagram for all observed times of maximum. Only the data points maxima 1–16 are marked, the later ones were shown in more detail in Fig. 2 and the broken curve represents roughly the smooth curve in Fig. 2. Since the estimated error in the epochs of maxima 1–16 is often as large as $\pm 150^d$ (due to the smoothing the individual maxima with a shorter duration were missed), we cannot recognize any significant cyclic behaviour. Further, it as has been noted above, we must have missed a lot of small amplitude maxima between the maxima 1–16.

Figure 2 suggests the presence of a beat cycle P_b = 21.6 yr, which could be caused by the interference of the stable primary period (P_0) of 371^{d}4 with a second cycle (P_1). P_1 can be computed with the formula: $1/P_b = |1/P_0 - 1/P_1|$, yielding $P_1 = 390^d \pm 2^d$. Thus, the ratio between the secondary cycle and primary stable period equals 1.05.

Next we investigated the short-time scale wavy pattern in Fig. 2. It shows a marginal significant second beat cycle of 4.7 yr with an estimated uncertainty of 10%. Then with the formula above, the possible third cycle $P_2 = 475^d \pm 3^d$ and the ratio between this one and the stable primary P_0 = 371^{d}4 amounts to 1.28. We will return to this ratio in Sect. 11. It is highly necessary that epochs of new maxima should be determined with a higher precision than 25^d to check the third cycle.

We conclude that the movement of LBVs in the HR-diagram lends support to our suspicion that both types of SD phases are provoked by radial pulsations: the normal SD phases by a stable pulsation and the VLT-SD phases by a longer lasting cyclic pulsation. The discovery of these two types of SD phases and their underlying pulsations throws a new light on the LBV phenomenon.

4. The duration/amplitude relation of the normal SD phases of AG Car

The behaviour of the duration of the normal SD phases and of the rising branch only as a function of the light amplitude is investigated with the aid of the data listed in Table 1 plotted in Fig. 4, left and right panel, respectively. They are marked with the numbers of the maxima.

As expected, there exists, a linear proportionality between the total duration of a normal SD phase (unbracketed numbers only) and the amplitude in V_J represented by the straight lines (after all: the larger the radius change, the more time it needs to recover). In Table 1, uncertain durations are left open, or are bracketed, such as all the early maxima 1–15, what we believe to be a combination of a few maxima with shorter durations ($<\sim 600^d$, see Fig. 4). Also maximum 16 is badly covered with observations and could consist of two SD phases. We presume that part of the scatter around the linear fit (through the unbracketed maxima) is caused by problems with overlapping of previous and following SD phases: the larger the radius variation and the light amplitude, the more chance of overlap. Also, the fact that most SD phases do not start and end from the genuine minimum state with minimum radius, say from around $V_J \sim 8.2$, but generally appear on top of a varying VLT-SD phase could give such problems. The exception is the sequence of low amplitude maxima 30–35 which begin and end near, what we presume to be, the genuine minimum brightness (the deeper minima after maxima 10 and 15, are based on visual observations and therefore less reliable). Thus, they are "independent" SD phases for which duration and amplitude are presumably undisturbed.

The relation between the total duration and amplitude for these "independent" SD phases appears to be different from that for the "dependent" ones: the dashed line illustrates that amplitudes of the latter are lower by roughly a factor 2 at the same total duration. In other words: near the genuine minimum

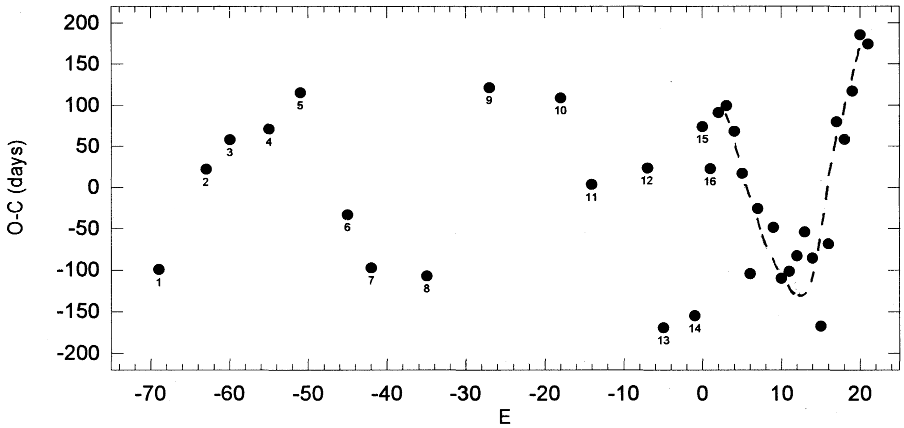

Fig. 3. The complete O-C diagram for all observed times of maxima for AG Car, applying the stable primary period of $371^{\rm d}4$. Numbers 1–16 refer to the maxima listed in the first column of Table 1. The estimated error in these data points amounts to $\pm150^{\rm d}$. The broken curve at the right represents the long-term wave in Fig. 2

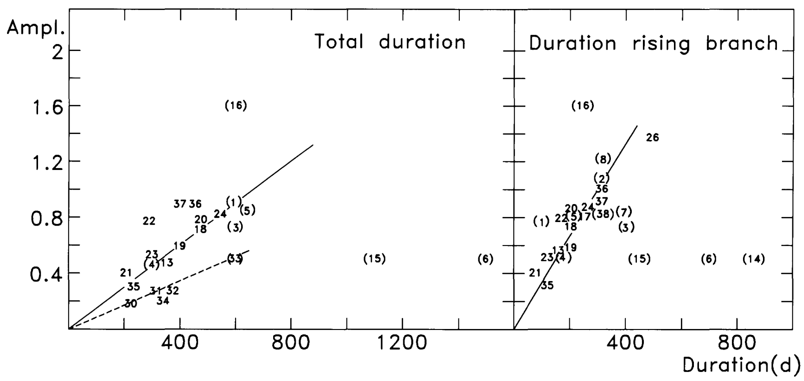

Fig. 4. The total duration and the duration of the rising branch of AG Car's normal SD phases (in days) versus the light amplitude. Instead of symbols the series number of the maxima listed in the first column of Table 1 is plotted

radius of AG Car, normal SD phases have amplitudes $\sim$ 2 as small as they would have on top of an ascending or descending branch of the VLT-SD phase. It must be noted that three of the six minima in this sequence are poorly covered by observations, but it is unlikely that this can account for the marked difference. The physical explanation for the systematic difference between the two groups is unknown. The opposite phenomenon is seen in the light curve of S Dor (Sects. 6, 7).

The right panel of Fig. 4 for the duration of the rising branch also shows a linear relationship, but for five of the six "independent" SD phases we have no reliable durations.

For AG Car we found no relation between the duration of the peak-to-peak interval and the amplitude of the preceding normal SD phase, a condition necessary to validate a comparison of the SD activity with a terrestrial geyser (Maeder 1992, Humphreys & Davidson 1994). Thus, apparently, it is not quite correct to make that comparison.

We conclude that durations of normal SD phases appear to be linearly proportional to the light amplitude in $V_{\rm J}$. Amplitudes tend to be lower as soon as SD phases are not influenced by neighbouring SD phases.

5. A comparison of temperature scales for the variations of AG Car

Temperature variations during the light variation can in principle be derived from spectral-type determinations, by a comparison of the colour index or the energy distribution with that of standard stars. A precise spectral type for AG Car has been assigned by Hutsemékers and Kohoutek (1988) at JD 43198 when $V_{\rm J}$ = 7.6, viz. B2–3Ib. In Fig. 1 this epoch is represented by a circle. The corresponding temperature is $\sim$ 17400 K (Schmidt-Kaler 1982).

Lamers et al. (1989) have studied the UV and visual energy distributions at nine different epochs with known $V_{\rm J}$ (represented by black dots in Fig. 1) when the star varied between $V_{\rm J}$ = 6.23 and 8.04. Using a set of supergiants as standards and correcting the energy distribution of AG Car with different reddenings until a best fit with one of the standards was obtained, they derived a consistent value for $E(B-V)_{\rm J} = 0.63\pm0.02$. For five of their epochs they also list their estimate of the bolometric correction (BC) from which we derived the corresponding temperature using Schmidt-Kaler's (1982) tables. This gives a range from 15800 K at $V_{\rm J}$ = 6.23 to 30000 K at $V_{\rm J}$ = 7.92. As expected the variations in $V_{\rm J}$ were equal to the variations in BC.

Leitherer et al. (1994) have analyzed the photospheric and wind parameters using an expanding, spherically extended non-LTE model atmosphere and derived stellar temperatures at nine epochs between 1990 and 1992. These epochs are indicated in Fig. 1 by small vertical arrows (some of them are at such a close distance in time that only one arrow is shown). At these epochs the $V_{\rm J}$ could be read off from the smooth curve.

For all the temperature determinations based on the works of Hutsemékers and Kohoutek (1988), Lamers et al. (1989) and Leitherer et al. (1994) we derived the intrinsic colour $(B-V)_{\rm J0}$ applying the tables of Schmidt-Kaler (1982). They are plotted

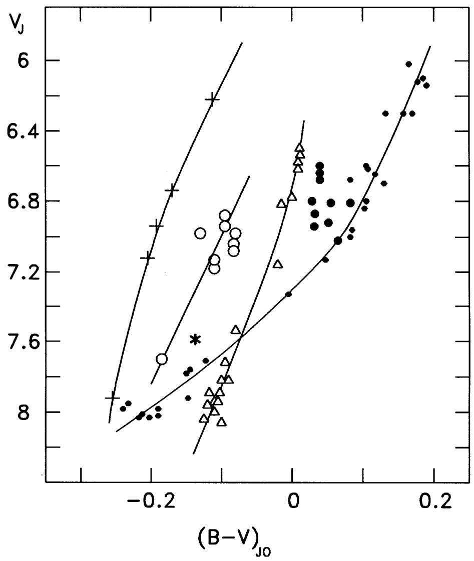

Fig. 5. The observed magnitude V_J versus the intrinsic colour $(B-V)_{J0}$ of AG Car. The two relations on the left (plusses, circles) and the asterisk are based on different temperature scales (see the text for details). The two relations on the right are based on the transformation of the observed $V-B$ and $b-y$ colour indices to the $(B-V)_J$ corrected for reddening (triangles and small dots, respectively). The large dots are obtained with an UBV photometer of which the $(B-V)_J$ is also corrected for reddening

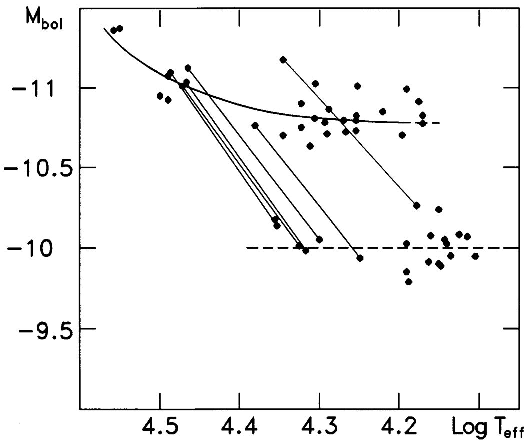

Fig. 6. The M_{bol} versus $\log T_{eff}$ diagram for a part of the light variation of AG Car based on the hot (upper part) and cool (lower part) temperature scale

in the observed magnitude/intrinsic colour diagram of Fig. 5 as an asterisk, plus signs and open circles, respectively. Evidently the Lamers et al. relation is based on higher temperatures than that for the other two types of temperature determination. The difference is of the order of 5000 K near minimum and 10000 K near maximum brightness. The comparison of observed and predicted colour variations for AG Car by de Koter (1993) also needed a high temperature to get a good fit. For example, according to this temperature scale the temperature between maximum at $V_J = 6$ and minimum $V_J = 8.2$ should vary between 14000 K and 32000 K, respectively. Near minimum ($V_J \sim 8.0$) at JD 46070 (marked with a thick vertical arrow in Fig. 1), Stahl (1986) classified AG Car as a Ofpe/WN9 star for which no temperature is known.

We cannot judge which temperature calibration, the "hot" or the "cool" scale, is the best. In order to investigate the effect of these scales on the assumption that M_{bol} should be constant with time during the SD activity we did the following. We transformed the colour indices $V-B$ (Walraven VBLUW system) and the $b-y$ (Strömgren system) into the $(B-V)_J$ (UBV system) (from JD 44597 onwards). We confined ourselves to averages of a group of observations which were made within a time span of at most one or two weeks. In a few cases we also used individual observations if there were large time gaps.

Both transformations were done with the appropriate relations given by Pel (1990) for $V-B$ and $b-y$. The one for $b-y$ differs not much from the one derived from eqs. (10) and (11) of Napiwotzki et al. (1993). Before we applied the transformation relation for $b-y$ we corrected for the interstellar reddening $E(B-V)_J = 0.63$ (Lamers et al. 1989) by using $E(b-y) = 0.777E(B-V)_J$ (Crawford and Mandwewala 1976). Then all these transformed $(B-V)_J$ values were plotted in Fig. 5 as triangles (from $V-B$) and small dots (from $b-y$) versus the observed magnitude V_J. Smooth slightly curved relations were sketched through the data points. As expected no consistent result is obtained, nor with each other, nor with one of the relations based on the temperature calibrations at the left of the diagram. The differences can amount to more than 0^m1 in $(B-V)_J$. The reason is that supergiants, such as AG Car, have a flatter energy distribution than normal stars (de Koter 1993) making a reliable transformation of colour indices impossible. As a comparison we also plotted as large dots the V_J and $(B-V)_{J0}$ values (the latter corrected for the reddening) directly obtained with an UBV photometer by Leitherer et al. (1994). They are also shifted with respect to the transformed relations. The transformation of V and y to V_J is obviously more reliable in view of the generally good fit of the simultaneously observed sections of the light curves of six LBVs discussed by Spoon et al. (1994).

Finally we derived a correction $\Delta(B-V)_{J0}$ for each data point based on the Walraven $V-B$ and the Strömgren $b-y$ with respect to the two relations at the left of Fig. 5. The Leitherer et al. (1994) relation has a much smaller range in $(B-V)_{J0}$. Consequently, only for V_J=6.6–7.8 (interval of the slightly extrapolated relation for their data points in Fig. 5) could the data points be corrected. From these new and "true" intrinsic colours, the temperature and BC could be derived and, with the distance of 6 kpc (Humphreys et al. 1989; Hoekzema et al. 1992), the M_v and M_{bol}.

Figure 6 shows a plot of the so obtained M_{bol} and T_{eff} for both temperature calibrations. It is the same diagram as for the LBVs S Dor and R71 = HDE 269006 made by van Genderen (1979) to illustrate that M_{bol} stayed more or less constant with time, independent of V_J and T_{eff} variations. A number of data points are connected by thin lines illustrating the position ac-

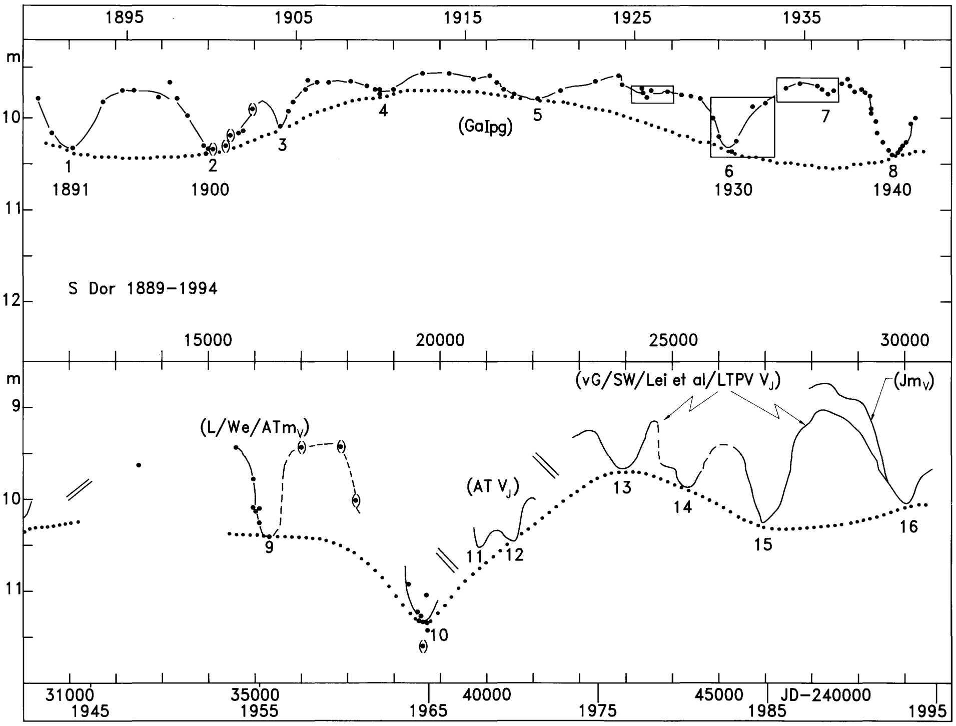

Fig. 7. The light curve of S Dor 1889–1994. Framed sections in the mean photographic part are given with more detail in Fig. 8. See the text for further explanation

cording to both calibrations. Those based on the "hot scale" tend to bend upward in contrast to those obtained on the "cool scale".

Thus, we conclude that either $M_{\rm bol}$ is in fact not completely constant (which is not surprising considering the result for S Dor, Sect. 9) and becomes brighter with higher temperatures, or the cool scale (or a scale in between) is better.

6. The light curve of S Dor

Figure 7 shows the schematic light curve of S Dor = HD 35343 = R88 comprising the time interval 1889–1994 and is based on the following sources:

1) The mean photographic light curve of Gaposchkin (1943) obtained between 1889 and 1940, in the Ipg magnitude scale marked with (Ga Ipg). Most of the dots represent an average of a number of plates, often 10 and sometimes 20 or 30 plates. Often they cover a time interval of weeks or even a month and longer, smoothing intrinsic short-timescale variations. The scatter is therefore small. Data points based on 1 plate only are bracketed. A smooth curve has been sketched through the data points. For the investigation of the scatter of the individual observations see below.

2) The visual ($m_{\rm v}$) and photographic (the Spg magnitude scale) data made between 1948 and 1956 by Wesselink (1956), Alexander & Thackeray (1971) and Lourens (1964). According to Wesselink (1956) the Spg scale can be transformed to the Spv scale by adding $0^{\rm m}2$. We applied this correction in Fig. 7. Further, according to Lourens (1964), the Ipg scale of Gaposchkin (1943) in point 1. can be translated to the Spg scale by adding $0^{\rm m}7$. Thus, a translation to the Spv scale still needs another $0^{\rm m}2$ making a total of $0^{\rm m}9$. This correction has been applied to Gaposchkin's light curve in Fig. 7 to make a comparison with the observations in the visual magnitude scale more easy. It appears that the Spv scale is close to the $m_{\rm v}$ scale, considering the close proximity of the data points with respect to each other in the light curve made by the various observers. Because we adopt $m_{\rm v} \sim V_{\rm J}$, we have $m_{\rm v} \sim V_{\rm J} \sim$ Spv. The individual observations were plotted in Fig. 7 and, where possible, connected by a smooth curve (partly broken if the trend is uncertain). These observations are marked with (L/We/AT $m_{\rm v}$).

3) The photoelectric $V_{\rm J}$ magnitudes (UBV system) made between 1967 and 1970 by Alexander & Thackeray (1971) marked with (AT $V_{\rm J}$).

4) Scattered photometry made in $V_{\rm J}$ of the UBV system and collected by van Genderen (1979, 1982), together with as yet unpublished observations made in the V passband of the VBLUW system of Walraven and transformed to $V_{\rm J}$, see Figs. 11a,b in Sect. 8. (In the second reference mentioned above (1982) only the first observation in Table 1 should be used, the others should be rejected). All these observations were made between 1970 and 1991. Further, scattered $V_{\rm J}$ observations made between 1974 and 1984 collected by Stahl & Wolf (1982) and Leitherer et al. (1985), and the uvby photometry by the LTPV group made between 1982 and 1992 and discussed by Spoon et al. (1994).

5) As a matter of interest we also show the smoothed hundred-day means of the visual observations made by Jones published by Bateson and Jones (1992) made between JD 47000 and JD 48700. We plotted them as a smooth curve in Fig. 7 marked with (J $m_{\rm v}$). According to them S Dor is a difficult object to observe visually because it is situated in a diffuse nebula. The

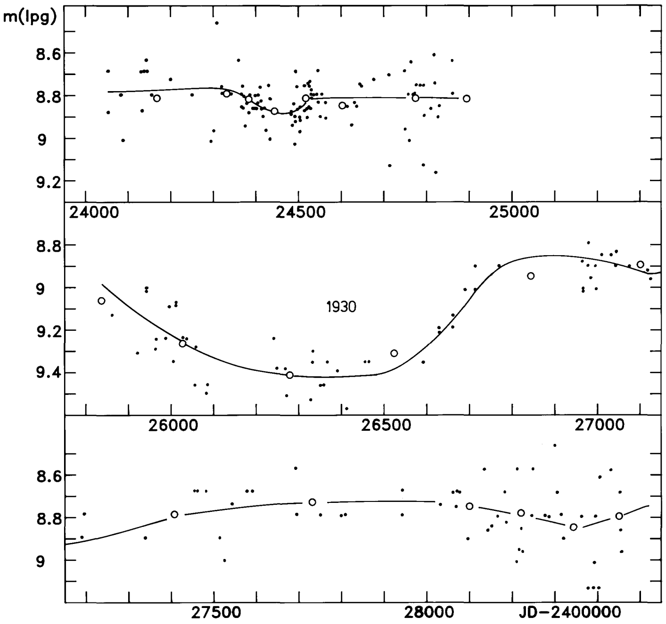

Fig. 8. The individual photographic observations (nightly averages) for three selected sections of the mean light curve of S Dor framed in Fig. 7

Table 2. Details of the minima of S Dor; see the text for definitions

No.	Min JD-2400000	E	Delta t (yr)	Alternative Min JD-2400000	Delta t'	V_J min
1	12000	0	0			10.3
2	15100	1	8.5			10.3
3	16500	2	3.8			10.1
4	18700	3	6.0			9.7
5	22000	4	9.0			9.8
6	26300	5	11.8			10.3
7	28300	6	5.5			9.8
8	29700	7	3.8			10.3
9	35400	9	(15.6)			(10.4)
10	38700	10	(9.0)			11.3
11	39900	11	(3.3)	40400	(4.7)	10.5
12	40700	11	2.2			10.4
13	43000	12	(6.3)		(7.1)	9.6
14	44400	13	3.8			9.8
15	46000	14	4.4			10.2
16	49100	15	8.5			10.0

visual magnitudes are brighter than the photoelectric ones, the difference decreases as S Dor declines in brightness, but the main features are the same. (It must be remarked that the photoelectric observations are not influenced by the nebula, since the sky background has always been taken at the same spot comprising only a very small area close to S Dor). Thus, visual observations, if numerous, are very useful to fill in the gaps of the photoelectric ones, as has been shown for AG Car in the previous sections.

6) New uvby observations made by the LTPV group in 1993 and 1994 and published by Manfroid et al. (1994) and Sterken et al. (1995). The smooth curve sketched through all the observations described in points 4) and 6) is marked with (vG/SW/Lei et al/LTPV V_J). See for a detailed light- and colour curve of the last large maximum between the minima 15 and 16 (1986–1994) Figs. 11a, b in Sect. 8.

We investigated the scatter in the individual photographic observations of Gaposchkin's (1943) data and where small light variations were smoothed away by using his averages. For that purpose three sections of his light curve were selected (framed in the upper panel of Fig. 7 around the 1930 minimum) and their individual observations (dots) plotted in Fig. 8; that is, the night averages, since on a number of nights several plates were taken. The circles in Fig. 8 are the average points according to Gaposchkin (1943). Sometimes the scatter amounts to $\pm 0^{m}3$, sometimes it is as small as $\pm 0^{m}1$. It appears that, when compared with the smooth curve sketched through the night averages, only little information is lost by taking averages. Light variations with timescales of 100^{d}–300^{d} are recognizable during the maximum stage.

7. Investigation of the cyclic behaviour of the SD phases of S Dor

As in the case of AG Car we sketched a smooth curve through the minima ignoring features with a time scale shorter than $\sim 4000^{d}$ (thinly dotted curve in Fig. 7). Considering this very-long-term behaviour, or VLT-SD phase, S Dor spent most of the time near maximum light, especially in the first half of 20th century, V_J(max) $\sim$ 9.5, with V_J(min) $\sim$ 10.4 (corrected to $m_v \sim V_J$). The time scale of the VLT-SD phase lies between 11000^{d} and 15000^{d}, or 30–41 yr.

In the second half of the 20th century maxima were alternated by deeper minima, with the deepest one at $V_J = 11.3$. There is no significant trend in the average brightness.

The epochs of the minima can often be better defined than those for the maxima because of their much shorter duration. Additionally, since the time scale of the normal SD phases is relatively long with respect to that of the VLT-SD phases (much longer than for AG Car), their shape is noticeably influenced by the slope of the VLT-SD cycle. The generally symmetric shapes of the normal SD phases (as in the case for AG Car), are distorted when they are superimposed on a steep branch of the VLT-SD phase: e.g. descending branches of the SD phases run less steeply when they appear on top of a rising branch of the VLT-SD cycle. Obviously, the normal SD phases of S Dor are not independent of the VLT-SD phases; it is as if the first ones are absorbed by the latter: the higher the brightness level of the VLT-SD phase, the smaller the amplitude of the normal SD phase and vice versa.

The epochs of the minima (estimated uncertainty of $\pm 150^{d}$) are listed in Table 2 with the series numbers (also indicated in Fig. 7), the Julian dates of the minima (depths $> 0^{m}2$ with re-

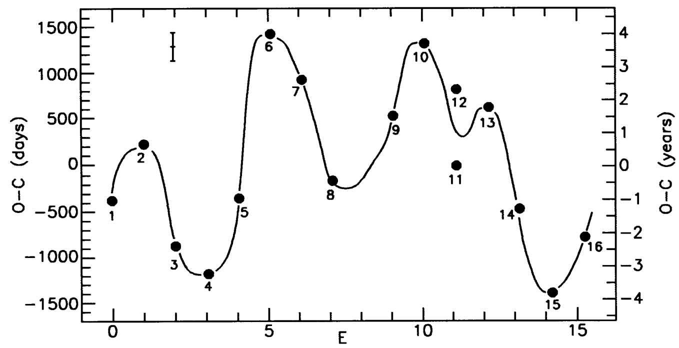

Fig. 9. The O-C diagram for the normal SD phases of S Dor applying the stable primary period of P = 2501^{d} (left Y axis), or 6.8 yr (right Y axis). The error bar amounts to twice $\pm 150^{d}$

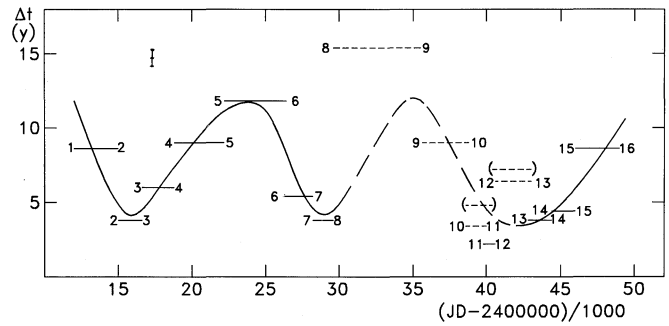

Fig. 10. The diagram Δt (t'), the time difference between two successive minima of the normal SD phases of S Dor versus date showing a few humps with a time scale of $\sim$ 40 yr. The error bar amounts to twice $\pm 212^{d}$

spect to one of the adjacent maxima and with a duration $> 500^{d}$), the cycle count E (see below), the time difference with the previous minimum Δt in years and the V_J(min). Blank lines indicate a time gap in the light curve. The corresponding Δt is bracketed, since it is possible that one or more minima were actually present in the gap and Δt may appear too long. It is possible that the two minima 11 and 12 should be considered as one minimum with the alternative epoch JD $\sim$ 40400, listed in the column "alternative Min". The corresponding time differences are listed in the column $\Delta t'$.

We obtain the least-squares ephemeris based on 16 times of minimum:

$$\begin{aligned} JD_{min} = &\ 12386 \quad + 2501^{d} E \\ &\pm 430 \qquad \pm 25^{d} \quad m.e. \end{aligned}$$

thus yielding P = 6.8 $\pm$ 0.1 yr. With one exception, the minima 11 and 12 which are separated by only 800^{d}, this formula allows to assign an unambiguous cycle number E to each element in the whole set of data.

Figure 9 gives the corresponding O-C diagram. The data points, connected by a smooth curve, are marked by the number of the minimum. The error bar represents the estimated uncertainty in the estimated epochs of $\pm 150^{d}$. It is clear that the points in Fig. 9 are not randomly distributed: though not rigidly strict, a cyclic pattern is visible. A least-squares sine fit to the O-C values yields a best-fitting cycle length amounting to $\sim$ 40 y, almost 15000^{d}.

The cyclic pattern of Fig. 9 is reproduced in Fig. 10 with a plot of Δt (t') versus date. The length of each horizontal line piece indicates the value of Δt (t') and is marked with the series number of the two minima. Broken horizontal line pieces refer to the bracketed Δt (t') values in Table 2. A cyclic curve has been sketched and is dashed where the trend is uncertain. The error bar for Δt (t') amounts to twice $\pm\sqrt{(150^2 + 150^2)} = \pm 212^{d}$.

For the alternative minimum at JD 40400, replacing the minima 11 and 12, one gets instead of the line pieces 10–11, 11–12 and 12–13, the two bracketed broken line pieces.

The result above indicates that the SD phases of S Dor are also subject to the possible interference of a stable primary period, 6.8 yr with a possible secondary cycle, like in the case of AG Car (Sect. 3). The result is a possible beat cycle of 40 yr with an estimated uncertainty of 10%.

The possible secondary cycle (P_1) can now be computed with the formula given in Sect. 3. It should be 8.2 yr $\pm$ 0.3 yr. The ratio between the possible secondary cycle and the stable primary period equals 1.21, which is remarkably close to the ratio found for the stable primary period and the third cycle of the normal SD phases of AG Car: 1.28. This commensurability is presumably not accidental, and is an additional proof for the pulsational explanation of the S Dor phases, see Sect. 11.

The possible beat cycle (40 yr) appears to be of the same order as the time scale of the VLT-SD phase (30–41 yr). This may be accidental. However, it is a fact that the light amplitudes are modulated with the VLT–SD cycles, see above. Such a behaviour is not seen in AG Car.

8. The fine structure of the 1985/1992 maximum of S Dor

To illustrate our point in Sect. 7 about ignoring small peaks and dips in the light curve with a time scale $\ll 500^{d}$ and amplitudes $< 0^{m}2$, we show in Figs. 11a and b the detailed light and colour curves for the 1985/1992 maximum of S Dor, in V_J and the colour curves. The V_J magnitudes (Fig. 11a) are partly based on the y magnitudes (y = V_J) of the LTPV project and partly on the transformed V magnitudes of the VBLUW system (not yet published).

There is an excellent agreement between both V_J values. The uncertainty in each data point is of the order of $\pm 0^{m}01$. The $(B-V)_J$ curve (Fig. 11a) is based on the transformed $V-B$ of the VBLUW system (scale at the right). All uvby data are based on the observations made by the LTPV group organized by Sterken (1983) (Manfroid et al. 1991, 1994; Sterken et al. 1993, 1995). Note that the magnitude scales in Fig. 11a are not always the same. In Fig. 11b we show the relative blue and ultraviolet light curves of the Strömgren and Walraven systems (the latter with the subscript W and also in magnitude scale) in order of decreasing effective wavelength.

A curve has been sketched through the data points, showing the "fine structure" of the last major SD phase. There is no significant difference between the rising and the descending

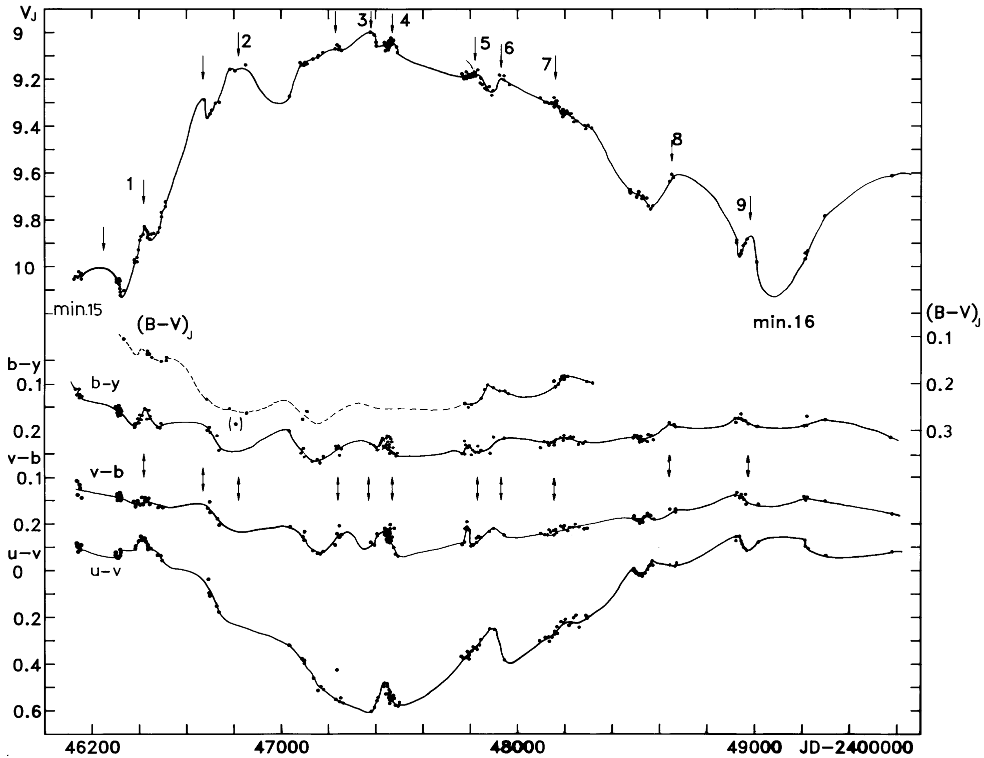

Fig. 11a. Fine structure of the 1985/1992 light maximum (between minima 15 and 16) of S Dor in $V_{\rm J}$ and the colour indices $(B-V)_{\rm J}$ (derived from the Walraven $V-B$) and of the Strömgren system

branch concerning the number of small peaks (in total ≈ 12 and marked by an arrow on top of the $V_{\rm J}$ light curve). Without doubt time gaps have influenced this statistic. In this light curve they have a duration of $\sim 100^{\rm d}$ and the amplitudes up to $0^{\rm m}2$. These amplitudes correspond to up to 20% of the stellar continuum flux in the $V_{\rm J}$ passband, which is rather substantial. There is no sign of any α Cyg-type variations as exhibited by e.g. AG Car, R71 and HR Car near minimum brightness (van Genderen et al. 1988, 1990) which have quasi-periods of the order of weeks and amplitudes also of at most $0^{\rm m}2$. The epochs of the peaks in the $V_{\rm J}$ light curve are indicated again between the $b-y$ and $v-b$ curves in Fig. 11a, to facilitate a comparison with the features in the colour curves. The arrows are also repeated in Fig. 11b.

The general trend during these 7 years is typical for an S Dor phase: red in the maximum and blue in the minimum. Shortly after the end of the rising branch in $V_{\rm J}$ the u curve even shows a deep depression down to only $\sim 0^{\rm m}2$ brighter than the brightness of minima 15 and 16. In the W passband (effective wavelength 3235 Å) the depression looks even deeper, but we have no good coverage of the two minima 15 and 16 in the Walraven photometric system to be completely certain.

The small peaks (and the adjacent dips) must be considered as changes of the stellar continuum light, because they are present (in varying strengths) in all passbands. Nine well-defined peaks are numbered 1 to 9. They have a wide range of characteristics. Peak 1 has a blue bump in the colour indices and can be called a "bright and blue" peak. Peaks 2 and 9 are red as well as the pairs 3–4 and 5–6, thus, they can be called "bright and red" peaks, while in between the colour is very blue. Peak 8 is only blue in $b-y$ and red in the other colours. In peak 7 the colours do not change. Thus, in half of the cases they are red in the maxima.

The time scale ($100^{\rm d}$) is not in contradiction with the expected time scale for normal α Cyg variables (variable super- and hypergiants non-LBVs) of the same spectral type as S Dor in maximum: A to F, see the P = constant lines in e.g. Fig. 14 in van Genderen et al. (1992).

9. A comparison of observed apparent magnitude ranges of AG Car and S Dor with those for a radius change during a horizontal displacement in the HR-diagram

In the early eighties it was still believed that an S Dor phase was mainly a stellar-wind phenomenon. From an attempt to extract from the photometric minimum and maximum state of the LBV R71 the luminosity of the dense expanding shell in the maximum state and adopting a non-variable stellar radius, van Genderen (1982) found a luminosity corresponding to a radius twice the stellar radius. The shell was treated as a normal stellar photosphere, i.e. optically thick. Since the star's spectrum shows P Cyg profiles during light maximum, its envelope cannot be optically thick and the conclusion at the time was that the photospheric radius could not be equated with that of the envelope and that the star itself could be variable.

Indeed, Leitherer et al. (1989) have shown for R71 and S Dor that the stellar radius varies drastically, even by a factor two. Later, de Koter (1993) and de Koter et al. (1996) confirmed this through a comparison of models with observations.

Thus, the presumed horizontal displacement in the $M_{\rm bol}/T_{\rm eff}$ diagram mainly reflects a stellar radius change. To what extent

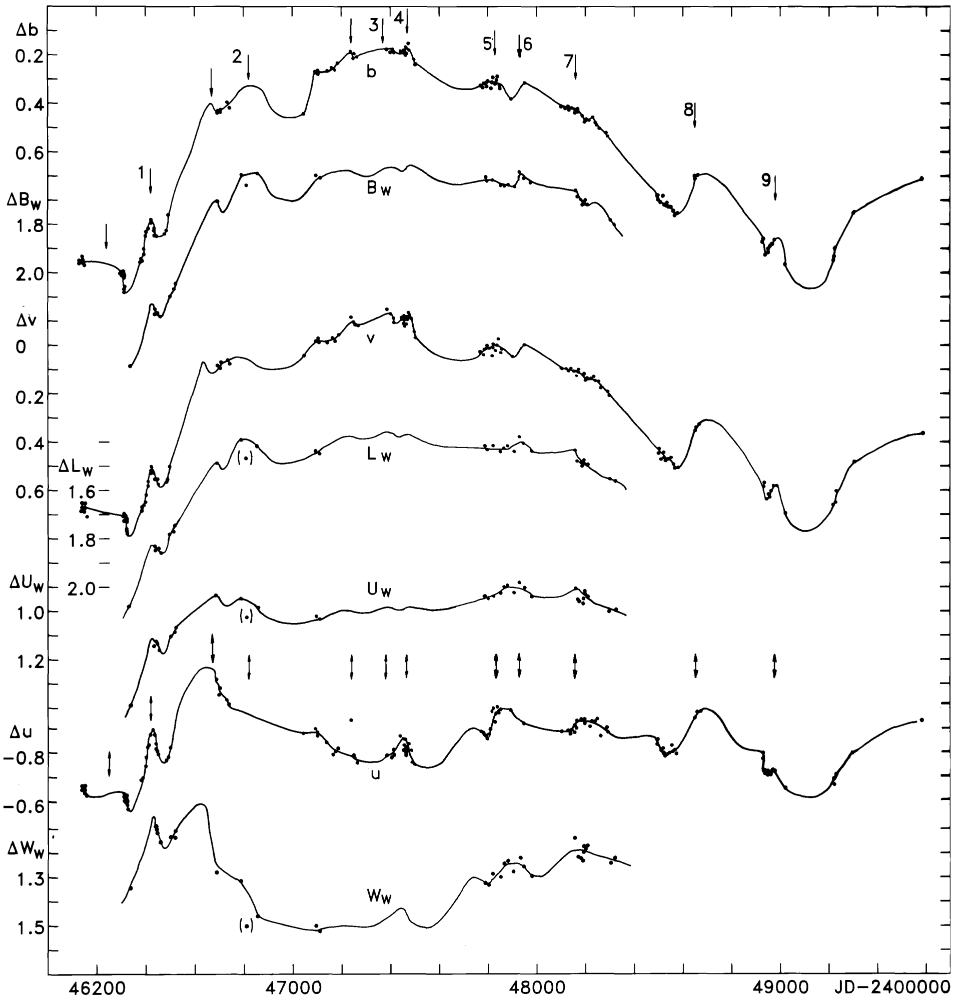

Fig. 11b. The same as for Fig. 11a but now for the blue and ultraviolet light curves (all in magnitude scale relative to the comparison star) of the Strömgren and Walraven systems, sorted in order of decreasing wavelength from top to bottom

the stellar wind of LBVs influences the radius change is not known and, anyway, such influence may differ from one LBV to another. If the radius change should be the major factor indeed, then the observed light ranges at various wavelengths between two epochs must be equal to the light ranges for horizontal evolution. This comparison can be made in a diagram of light ranges versus wavelength.

Thus, first one chooses two points in the light curve of an LBV for which the spectral type can also be deduced, e.g. from the intrinsic colour $(B-V)_{J0}$. However, one should also keep in mind that for extended atmospheres this may not be without uncertainties. (Better would be, if we could use reliable temperature determinations, see discussion below for S Dor). For AG Car this has been done with the aid of Fig. 5: from V_J follows $(B-V)_{J0}$, which depends of course of the chosen relation. Then, from tables of intrinsic colour versus spectral type, the ranges in the apparent magnitudes can be computed as if the star evolves at constant M_{bol} between the two spectral types derived above. The longer the wavelength range the better. Therefore, we tried to select pairs of points in the light curve where near-infrared observations have also been made (Whitelock et al. 1983; Carter et al. 1992), but this was not always possible.

We consulted the photometric tables of Johnson (1968) for O9.5–A0 Ia stars and the photometric passbands UBVRI, the tables of Schmidt-Kaler (1982) for A2–F5 Ia stars and the passbands UBV, and the tables of Koornneef (1983) for O9.5–F5 Ia stars and the passbands JHKL.

Then, by adopting an arbitrary value for M_{bol} for all spectral types and a value for the BC for each of these, M_v could be computed. Since M_v is equivalent to V_J, the corresponding arbitrary apparent magnitudes in all passbands as well as their amplitudes (Δm) can be calculated with the aid of the intrinsic colours.

Table 3 lists for AG Car three selected pairs of points along the light curve. By applying Fig. 5 for AG Car we made use of the reddening correction of Lamers et al. (1989).

Figure 12 shows the observed and the evolutionary ranges (for two temperature scales, see below) as a function of $1/\lambda\mu m^{-1}$ for AG Car. The Walraven passbands VBLUW are marked with the subscript "W", the Johnson UBV passbands with the subscript "J". We derived the spectral types of the selected points along the light curve by using the "hot" as well as the "cool" temperature scale sketched in Fig. 5. The intrinsic colour $(B-V)_{J0}$ is transformed into a spectral type with the aid of the tables of Schmidt-Kaler (1982) and the spectral types

Table 3. Particulars of the chosen pairs of points for AG Car

JD-2400000	Range in V_J (mag)	Photometry	References
44597–44633	0.33 (rising br.	VBLUW	van Genderen et al. 1988
	to max. 26)	K	Carter et al. 1992
45717–46146	0.87 (desc. br	VBLUW	van Genderen et al. 1988
	after max 27)	K	Carter et al. 1992
47137–47315	0.30 (rising br.	VBLUW	van Genderen et al. 1990
	to max. 33)	K	Carter et al. 1992

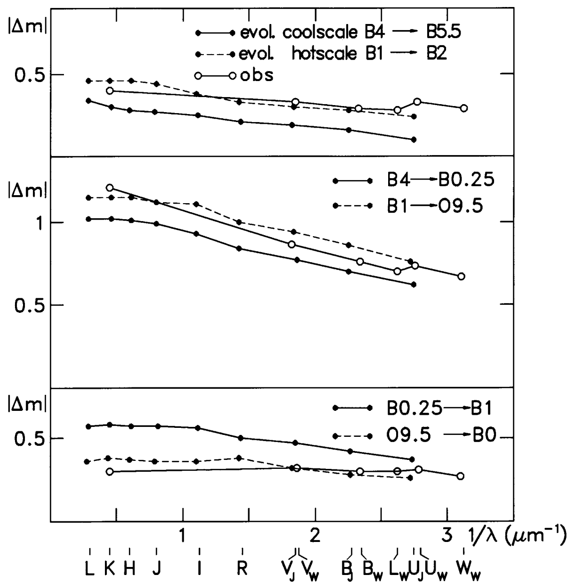

Fig. 12. The observed ranges of the apparent magnitudes compared with the evolutionary ranges for three pairs of points along the light curve of AG Car for the intervals listed in Table 3

into a temperature by using the tables of de Jager and Nieuwenhuijzen (1987), although on the average those of Schmidt-Kaler give similar results. The BC is taken from the tables of Schmidt-Kaler (1982). The spectral ranges found are indicated in the right upper corner of the three panels. The respective Julian dates of the pairs are listed in Table 3. The conclusions are as follows:

1. the best agreement between ΔBC and ΔV_J is obtained for the hot scale, the differences are at most 0^m04. For the cool scale the differences lie between 0^m1 and 0^m2 (positive as well as negative). After all, for horizontal evolution in the theoretical HR diagram, ΔM_v = deltaV_J = $-\Delta BC$, because M_{bol} = $M_v - BC$ = constant.
2. ΔV_J (obs) agrees best with ΔV_J (evol) for the hot scale as can be seen in Fig. 12.
3. with the possible exception of the results in the lower panel, the slopes for both evolutionary relations are in reasonable agreement with the observations, but those for the hot scale are somewhat better. However, this conclusion has only a meaning, if we expect that the radius change during an SD phase is the major cause of temperature and colour variation (this is substantiated by the parameter study of the typical SD phase by de Koter et al. (1996) and that we are indeed dealing with a more or less horizontal displacement in the theoretical HR diagram.

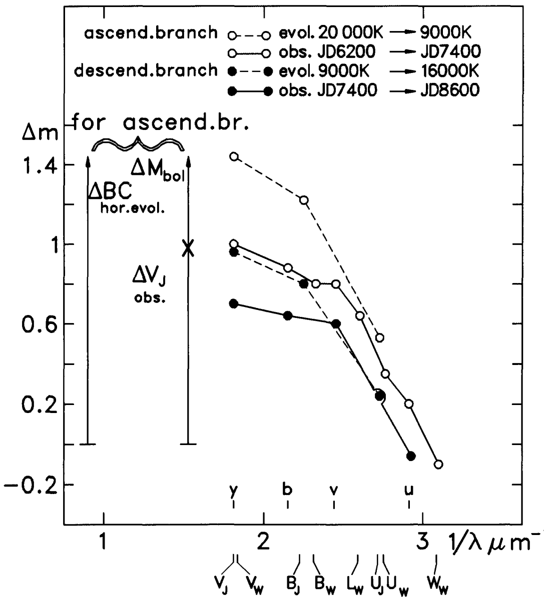

Fig. 13. The observed ranges of the apparent magnitudes compared with the evolutionary ranges for an ascending and a descending branch of an SD phase of S Dor

We can conclude that the observed variation in the apparent magnitudes of AG Car supports a radius variation and a more or less horizontal displacement (at least within a few 0^m1) and that the influence of the extended atmosphere is of minor importance on the photometric characteristics.

For S Dor we followed a different approach. We made use of three dates of the modelling of the photometric variations of S Dor by Vennix et al. (quoted by Lamers 1995). The model predicts amongst others the trend of the temperature during an S Dor phase. From these presumably reliable temperatures can be deduced the spectral types and the BC's (we are still aware that LBV atmospheres are not normal and that this method can introduce errors, but it appears that the results are in close agreement with the conclusions of Vennix et al. (see Lamers 1995).

The dates (minimum 15, maximum and minimum 16) and the respective temperatures, spectral types and BC's are as follows: JD 46200 (20000 K, B1.5, −1.75), JD 47400 (9000 K, A2, −0.3), JD (16000 K, B3, −1.3). At those dates Strömgren photometry were made by the LTPV group (Manfroid et al. 1991) and partly Walraven photometry, and plotted in Fig. 13 (circles and large dots connected by straight lines). Then, the evolutionary ranges (UBV system) were derived with the estimated spectral types and plotted in Fig. 13 with the same symbols, connected by broken lines. Obviously there are differences between the two. For the horizontal evolution the ranges in V_J for example, are larger by 0^m3 and 0^m45 than the observed ranges

(0^m7 and 1^m0, respectively). In Fig. 13 is explained how this should be interpreted. For a horizontal displacement we expect ΔV_J(obs) = ΔV_J(hor.displ.) = $-\Delta BC$. We observe e.g. that the first term for the ascending branch is smaller by 0^m45 than the third term. Thus, M_{bol} becomes fainter with the same value during the displacement to the right of the HR diagram! This is in very close agreement with the result of Vennix et al. (quoted by Lamers 1995): 0^m5.

A rough estimation to determine the range in M_{bol} from the deep 1965 minimum (V_J = 11.4) to the maximum in 1989 (JD 47400) (V_J = 9.0) even results in $\sim 1^m$. This has been found as follows: the estimated colour in that minimum, ~ -0.1, is based by extrapolation of the $(B-V)_J$ curve in Fig. 4 of van Genderen (1979). In maximum that colour amounts to 0.28. The corresponding T_{eff} = 9000 K (Lamers 1995) for which $(B-V)_{J0}$ = 0.05 (Schmidt-Kaler 1982), thus, the reddening $E(B-V)_J$ = 0.23. The Walraven photometry revealed a reddening 0.17 (used by van Genderen 1979), thus, we choose 0.20 as the best reddening value. Stahl & Wolf (1982) and Leitherer et al. (1985) used $E(B-V)_J$ = 0.05, while the study of the galactic foreground reddening based on IRAS data revealed $0^m09 \pm 0^m03$ in the direction of S Dor (Schwering & Israel 1991), their Fig. 7b). Since there should also be foreground reddening in the LMC, the latter value must be considered as a lower limit.

Consequently, applying the reddening 0^m20 and the distance modulus 18.6 for the LMC we arrive at M_{bol}(min. 1965) = -11.3 and M_{bol}(max. 1989) = -10.3, with an estimated uncertainty in both values of 0^m3. This range amounting to 1^m also supports an outspoken non-horizontal displacement for S Dor in the theoretical HR-diagram during an SD phase.

10. Investigation of the cyclic behaviour of the SD phases of Eta Car

The identification of the VLT-SD activity as a significant part of the overall activity of the two LBVs AG Car and S Dor has important consequences for the interpretation of the long-term light and colour variation of Eta Car. After all, Eta Car turned out to be a normal LBV in various respects (e.g. van Genderen & Thé 1984, van Genderen et al. 1994, Humphreys & Davidson 1994). Suppose that the secular brightness increase of Eta Car during the last decades was partly caused by an ascending branch of a VLT-SD cycle (star moves to the right in the HR-diagram), then we must find an explanation for the absence of the expected reddening. There is even a slight net blueing of the colours over the last 20 yr (van Genderen et al. 1994, 1995). This is indirect support for the explanation presented by us that the secular brightness increase should be partly due to the decrease of the extinction in front of the LBV and within the expanding bipolar nebula, causing a blueing of the colours. Obviously, the brightening of the star through the decrease of the extinction is accompanied by a brightening due to the expansion of the star. The effect on the star's colour through the decrease of the extinction is stronger than that through the radius increase, resulting in a net blueing. Thus, to our model for the explanation of the observed net variation in a wide wavelength range over the last 20 yr, can be added some reddening contribution of the ascending branch of the VLT-SD cycle (Fig. 12 in van Genderen et al. 1994).

Consequently, the suggestion that Eta Car might be evolving perceptibly within a few decades to the right in the HR-diagram (Whitelock et al. 1994; Damineli 1996), violating theoretical timescales for evolving massive stars (e.g. Maeder and Meynet 1987; Stothers & Chin 1993, 1994; Kiriakidis et al. 1993), can now be replaced by a physically more realistic VLT-SD displacement to the right in the HR-diagram (thus a slow expansion of the star), which is only a temporary phenomenon. The decrease of the He I 10830 equivalent width over the last 13 yr (1981–1994) found by Damineli (1996) is not in contradiction with this scenario. The time scale of such a movement is difficult to estimate, but must be at least in the order of a few decades.

A periodic (normal) SD cycle of 5.52 yr has been claimed by Damineli (1996) by using the recent maxima in the optical and near-infrared light curves, the trend of the equivalent width of the He I 10830 line (three maxima) and three historical optical maxima from the previous century (1827, 1838 and 1843). However, we have some doubt about the reliability of this periodicity. The first objection concerns the two maxima in 1985 and 1986, one year apart, which are counted as one maximum in the near-infrared light curve by Whitelock et al. (1994; see van Genderen et al. 1995). The second objection concerns the way in which the light maxima were selected: generally only in the bright phases of Eta Car and not in the descending branch after 1850 and in the subsequent deep minimum. There is no reason to do that. We have shown in the case of AG Car and S Dor that normal SD phases occur on top of all phases of the VLT-SD cycles. Further, all other observed maxima in the light curve in the following decades up to 1975 were omitted. Indeed, most of them do not fit the proposed period of 5.52 yr, viz. the maximum (this one occurs in the bright phase also) at 1856.2 (or JD 2393105, $E = -24.7$, amplitude 0^m7, Innes 1903, see also Fig. 2 of Damineli 1996), the very prominent maximum at 1890.0 (or JD 2411368, $E = -18.57$, amplitude 1^m5, Innes 1903), the maximum at 1952.2 (or JD 2434091, de Vaucouleurs & Eggen 1952) and five of the six maxima in the 1952–1973 light curve discussed by Feinstein & Marraco (1974, partly collected by the visual observers A.F. Jones and F. M. Bateson). The small maximum of 1870.7 (or JD 2404275, Innes 1903) fits more or less: $E = -22.1$.

Similar to AG Car and S Dor, there may be some sort of a stable periodic SD cycle, but it appeared to be difficult to make a proper analysis due to other variable constituents of the Eta Car system and the many time gaps in the sequence of photoelectric observations.

Figure 14 shows the plot Δt versus date for all maxima between 1827 and 1994 listed in Table 4. The maxima based on the scattered photographic photometry of O'Connell are highly uncertain and therefore bracketed. Evidently, a lot of low amplitude maxima were missed in the early days. Therefore, the Δt values at that time appear to be so large compared to those of the last decades for which the time scale lies between 1 and 3 yr. No proper cyclic behaviour is evident in Fig. 14. Not surprisingly,

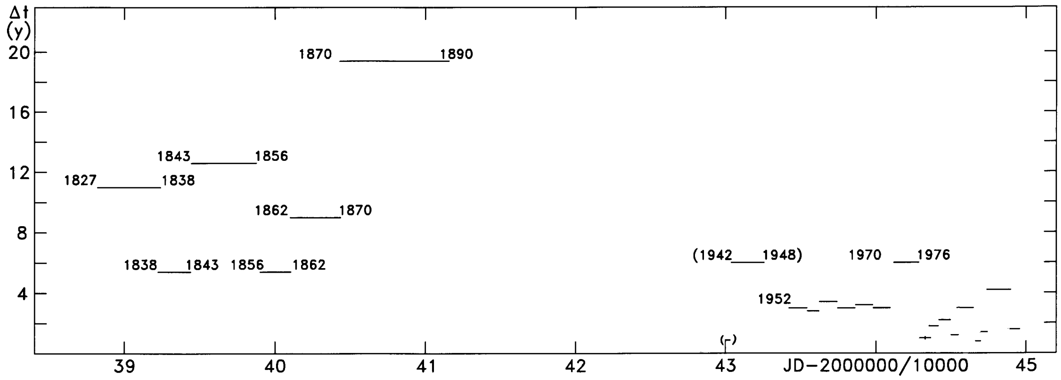

Fig. 14. The diagram Δt, the time difference between two successive maxima, of Eta Car, versus date for the interval 1827–1994

Table 4. The identified maxima of the normal SD phases in the light curve of Eta Car 1827–1994

Year	JD	Δt (yr)	Reference
1827	2 388 361	0	Innes 1903
1838	2 392 385	11.02	
1843	2 394 402	5.52	
1856	2 399 022	12.65	
1862	2 401 019	5.47	
1870	2 404 275	8.91	
1890	2 411 368	19.42	de Vaucouleurs and Eggen 1952
1941	2 430 140	(51.39)	O'Connell 1956
1942	2 430 480	(0.93)	
1948	2 432 712	(6.11)	
1952	2 434 091	3.78	de Vaucouleurs and Eggen 1952
1955	2 435 180	2.98	Feinstein and Marraco 1974
1957	2 436 200	2.79	
1961	2 437 400	3.29	
1964	2 438 450	2.87	
1967	2 439 600	3.15	
1970	2 440 700	3.01	
1976	2 442 900	6.02	van Genderen et al. 1994,
1977	2 443 250	0.96	1995; Whitelock et al. 1994;
1978	2 443 600	0.96	Sterken et al. 1996
1980	2 444 245	1.76	
1982	2 445 010	2.09	
1983	2 445 423	1.13	
1986	2 446 571	3.14	
1987	2 446 870	0.82	
1988	2 447 345	1.30	
1992	2 448 933	4.35	
1994	2 449 527	1.63	

Feinstein and Marraco (1974) suggested a three year period on account of the maxima observed between 1955 and 1970, see Fig. 14.

Also, Whitelock et al. (1994) concluded from an analysis of 20 yr of near-infrared photometry, that one can only speak of a quasi-periodicity for prominent maxima in the H passband. As explained above there is a problem concerning the one maximum around JD 2446700 which consists of two prominent maxima (due to the lower time resolution of their data this double maximum has been counted as one). Actually, this double maximum emerges in Whitelock et al.'s (1994) model simulation shown in their Fig. 5 upper panel.

Table 5. Time scales and approximate amplitudes (in V_J) of the VLT-SD phases of AG Car and S Dor

Star	Time scale (decades)	Ampl. (mag)
AG Car	2.5	1–2
S Dor	3.5	1–2

It has been demonstrated by Sterken et al. (1996) that most of the SD maxima of Eta Car coincide with the maxima of the $58^{d}58$ stable periodicity of the α Cyg-type variations (amplitudes up to $0^{m}05$) and that this periodicity possibly beats with another one on a time scale of 20 yr.

11. Discussion and conclusions

From our study comprising a century of photometric observations, it appears that the S Dor (SD) activity, characterized by radius-, temperature- and light variations, of AG Car and S Dor is caused by two types of SD phases.

The first one has a time scale of decades and is called the very-long-time scale SD (VLT-SD) phase. On top of this VLT-SD phase are superimposed numerous "normal" SD phases. They occur with varying amplitudes and generally with a symmetric shape. Their light amplitudes and durations for AG Car are apparently not correlated with the phase of the VLT-SD cycle, contrary to S Dor (Fig. 7). It should be noted that Kiriakidis et al. (1993) identified two internal layers in the models of massive stars prone to instability.

An important discovery is that these normal S Dor phases of AG Car and presumably also of S Dor, are subject to a stable pulsation period over a time interval of one century. Cyclic patterns in the O-C values point to the possible presence of more cycles interfering with the stable primary period producing beat cycles.

Tables 5, 6 summarize timescales, periods and mean errors, beat periods and estimated errors, second and possible third cycles and their ratios. In the best covered parts of its light

Table 6. Periods (or cycle lengths) and their errors, approximate amplitudes (in V_J), and period ratios of the normal SD phases of AG Car and S Dor

Star	P_0	Ampl. (mag)	First P_b	P_1	P_1/P_0	second P_b	P_2	P_2/P_0
AG Car	371^d4 $\pm 0^d6$	0.2–1.5	21.6 yr $\pm$2.2 yr	390^d $\pm 2^d$	1.05	4.7 yr 0.5 yr	475^d $\pm 3^d$	1.28
S Dor	6.8 yr $\pm$0.1 yr	0.5–1.2	40 yr $\pm$4 yr	8.2 yr $\pm$0.3 yr	1.21			

curve AG Car shows a possible beat cycle of 21.6 yr. S Dor's cyclic pattern in the O-C values possibly shows three humps on a time scale of about 40 yr. Note however, that such a pattern may also arise as the consequence of irregular data sampling.

The ratios between the possible third cycle (P_2) and the stable primary periods (P_0) for AG Car and between the second cycle (P_1) and the presumably stable primary (P_0) for S Dor, are nearly equal, viz. 1.25 ± 0.04, or $\sim$ a ratio 5/4. Bezdenezhnyi (1994a) carried out a Fourier analysis of photometric data of the RR Lyrae star AE Boo and concluded that the light variations can be well described with the fundamental frequency, the first and second harmonic, and two more frequencies at 5/4 and 3/2 times the fundamental frequency. In a subsequent paper Bezdenezhnyi (1994b) presents a table with pulsation periods and identifications for 13 δ Scuti stars, and concluded that, similar to RR Lyrae stars, frequencies in the light variations of δ Scuti stars are close to 3/2 and 5/4 times the fundamental frequency. Three stars in his Table 2 (viz. HQ Hya, LT Vul and 10 NGC 6871) yield a mean period ratio of 1.22 ± 0.03, exactly the value we find for S Dor and AG Car, which supports our interpretation of pulsational origin of the SD phenomenon!

It has been established by various researchers that the excursions in the theoretical HR-diagram during an SD phase are more or less horizontal (within a few 0^m1). Our findings for AG Car supports this view, contrary to those of S Dor. Similarly to Vennix et al. (quoted by Lamers 1995), we find that S Dor has a much higher luminosity in minimum than in maximum. We find ranges in V_J amounting to 0^m7, 1^m and 2^m4 corresponding to ranges in M_{bol} amounting to 0^m3, 0^m5 and 1^m, respectively.

Durations of the normal SD phases show a linear proportionality with the light amplitude (in V_J). The comparison of SD phases, especially the normal ones, with a terrestrial geyser does not seem quite correct (Sect. 4).

Episodes of dramatic mass loss resulting in ejections of thick clouds and shells and accompanied by brightness variations of more than 3^m, could with good reasons be called "eruptions" or "outbursts." Whether such episodes occur when exceptionally high maxima of VLT-SD and normal SD phases coincide, is unknown. However, we presume that some type of additional violent energy output is necessary to explain the M_{bol} decrease (is a luminosity increase) by 1^m–2^m during the "eruptions" of Eta Car in 1843 (van Genderen & Thé 1984) and P Cyg in the 17th century (de Groot & Lamers 1992), see also Davidson (1989) and Humphreys & Davidson (1994). The time scale for such eruptions seems to be of the order of centuries or more.

Investigating 167 yr of photometric observations of Eta Car, revealed no convincing evidence for a period for the normal SD phases, contrary to suggestions made in the literature. During the time of photoelectric monitoring, the time scale for the normal SD phases lies between 1 and 3 yr. There are strong indications that during the last decades Eta Car experienced an ascending branch of a VLT-SD phase. This indirectly supports our view that a decrease of circumstellar dust density also occured during that time (Sect. 10). The reason is that the net colour change during the last 20 yr is not red as it should be for a movement to the right of the HR-diagram, but slightly blue (van Genderen et al. 1994, 1995).

The sources of the normal and VLT-SD phases are likely to lie at different levels in the stellar interior. Theoretical research with an emphasis on pulsation models is required to explain our new results. Violent pulsational instabilities have been discovered in very massive stars by e.g. Kiriakidis et al. (1993). Dynamical strange-mode and mode-coupling instabilities were identified and are associated with the LBV area in the HR-diagram.

Langer et al. (1994) developed a novel evolutionary scenario by introducing "pulsational driven mass loss" (in addition to the radiation pressure driven wind), which is thought to be provoked by the above-mentioned violent pulsational instabilities.

Other theoretical studies on the SD phenomenon exists, like those of Maeder (1992), Glatzel & Kiriakidis (1993) and Stothers & Chin (1993, 1994, 1995). The latter authors for example, have discovered a new type of stellar-envelope structure for very massive stars. They found a mechanism for the dynamical instability responsible for the SD phases (called by them "episodes of high mass loss", (which according to de Koter et al. 1996 and references therein, is not necessarily the case). Their models predict "periods". For AG Car, S Dor and Eta Car they used 9, 19 and 4 yr, respectively. According to our analysis, only the one for Eta Car is not far from the truth. Besides we have the problem which period (or time scale) should be chosen: that of the VLT-SD phase, or the one of the normal SD phase (although the inverse proportionality of the periods of the normal SD phases of AG Car and S Dor with the luminosity is not invalidating Stothers & Chin's (1995) result).

It appears that the "α Cyg-type variations" only occur (or at least are clearly detectable) when the LBVs are near low brightness (amplitudes $\sim 0^m1$ and quasi-periods of 2–6 weeks). These micro variations should not be mistaken with the low amplitude SD phases! The colour variations of both phenomena are different; see Sect. 2. Generally it is believed that the cause of the α Cyg-type variations are non-radial pulsations, but Cox et al. (1995) favour radial pulsations. Whether they are related with the low order modes exited by mode interactions, found by Gautschy's (1992) non-radial and non-adiabatic stability analysis for α Cyg variables is unknown.

So far, no α Cyg-type variations were found in S Dor. The low amplitude variations found during the minima 15 and 16 (in 1985 and 1993, respectively) are different (see below), because the VLT-SD phase is far from the genuine minimum brightness.

The low-amplitude variations just mentioned not only occur in minima 15 and 16, but also in the maximum in between. They have a time scale of $\sim 100^{\rm d}$ and amplitudes up to $\sim 0^{\rm m}2$. Colour variations are diverse, but in half of the cases they are red in the maxima and blue in the minima. Leitherer et al. (1985) and Wolf & Stahl (1990) suspected the presence of pulsation like motions on a time scale of a few months and depth dependent velocity fields during S Dor's maximum. These suspicions are based on emission line variations and reversed P Cyg profiles. So far, it is unknown whether their observations are really correlated with the observed photometric variations.

Since S Dor in maximum has a super-/hypergiant spectral type A-F, we could perhaps learn more about the source of its low amplitude variations relative to the micro variations of normal α Cyg variables of roughly the same spectral type, by a careful comparison of simultaneous spectroscopic and photometric observations. The A3 and F8 type hypergiants HD 33579 and HDE 271182 (= R92 = G266), both also in the LMC, are such examples. Their micro variations are roughly of the same amplitude and time scale (van Genderen 1979; van Genderen & Hadiyanto Nitihardjo 1989) as the low amplitude variations of S Dor. However, the colours of HD 33579 are generally blue in the light maxima and red in the minima, while for S Dor the colour variations are only in half of the cases like that. It should be noted that the analysis of the light and colour variations of HD 33579 are not in favour of any type of pulsation (van Genderen 1979).

Epilogue

We want to pay tribute to the numerous dedicated (amateur) astronomers of the Variable Star Section of the Royal Astronomical Society of New Zealand, whose thousands of visual observations of AG Car and S Dor were of crucial importance for the completion of the light curves when photoelectric observations were interrupted by large gaps in time. Without those observations numerous SD phases would have been missed in the light curve of AG Car, making a proper analysis of the periodicity more difficult, if not impossible.

Many types of peculiar variables, such as the S Dor- or Luminous Blue Variables, are of crucial importance for understanding particular phases of stellar evolution. A better understanding depends crucially on continuous and dedicated monitoring, whether done by professionals or amateur observers. The possibilities for monitoring campaigns by professionals is *declining* as a result of the fact that some observatories decrease the number of small telescopes in favour of large ones, which cannot be used for these purposes. This is a matter of serious concern. Therefore we encourage amateurs all over the world never to cease observing peculiar variable stars and to go on making those data available to the scientific community, even if their equipment is modest. The erection of more automatic photoelectric telescopes, also in the southern hemisphere, would be highly necessary.

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