ASTRONOMY
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Cyclicities in the light variations of Luminous Blue Variables[*]

II. R 40 developing an S Doradus phase

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Abstract. Strömgren differential photometry of R 40 collected during the time interval 1986–1996 is analysed together with Walraven photometry. The gradual brightening of the star over the last 10 years can be described by a linear trend with superimposed oscillations (in v, b and y) with frequency 0.0008 cd^{-1} ($\sim$ 1300 d cycle). We interpret these oscillations as "normal S Dor" phases, and suggest that the quasi-linear brightening of the star is the ascending branch of a growing very-long-term S Dor phase (VLT–SD), as found by van Genderen et al. (1997a) in AG Car and S Dor itself. As R 40 is now becoming fainter and bluer, the length of the VLT–SD cycle is about 20 years.

Key words: stars: individual: HD 68884= R 40(SMC) – stars: variables: other – supergiants – stars: oscillations – Magellanic Clouds

1. Introduction

Luminous Blue Variables (LBVs) are massive early-type stars exhibiting spectroscopic and photometric variability with different time-scales. Their photometric variability is, generally, described as semi-regular or semi-periodic. However, recent evidence (Sterken et al. 1997, van Genderen et al. 1997a,b) suggests that this photometric variability may be described by the combined effect of multi-periodic oscillations and some degree of stochastic variability. In particular, Sterken et al. (1996) demonstrate the existence of a stable pulsation period of 58 days in the case of η Car, while van Genderen et al. (1997a,b) describe the existence in most LBVs of two kinds of S Dor phases, viz. normal (**SD**) phases and, as they define, very-long-term (**VLT-SD**) phases. Both kinds are of a recurrent nature—that is, their appearance is not periodic, but cyclic. The evidence for the existence of both kinds of oscillations comes from an analysis of several decades (to more than one century) of photometric observations and magnitude estimates. The study of these oscillations in LBVs is an important tool for understanding their internal and/or atmospheric structure and the role they play in the episodic mass-loss events displayed by these objects.

The LBV character of R 40 (HD 6884, $V \sim 10.3$, AIa$^+$) was discovered by Szeifert et al. (1993) as the star had become brighter in the visual range by about $0\overset{\mathrm{m}}{.}5$ between 1986 and 1993; the brightening was accompanied by a change in spectral type from B8Ie in the late 1950s to A3Ia-O in 1993, the true signature of an LBV turning cooler when becoming brighter while going through a (mild) active phase (or S Dor phase in the nomenclature conceived by van Genderen et al. 1997a). Szeifert et al. (1993) discerned a quasi-period of about 120 days, and assigned the fundamental stellar parameters $T_{\rm eff} = 8700$ K, $\log g = 0.75$, $M_{\rm bol} = -9.4$, $R/R_\odot = 280$ and $M/M_\odot = 16$.

R 40 is a touchstone in two respects. First of all, its brightening during the last decade allows the study of the microvariations of an LBV in a stage intermediate between quiescence (hot early-type [pre-]LBV) and maximum state (cool star surrounded by a slowly-expanding envelope implying spectral type A) while roughly maintaining a constant bolometric magnitude. In addition, the study of such an object may lead to an answer to the question whether the microvariations during maximum light are of a different nature from those seen in quiescence (see the analyses by van Genderen et al. 1997a,b).

In this paper we present a study of the light variations of R 40 involving all available photometric data originating from photometric monitoring during the last 15 years, including data that were not available at the time Szeifert et al. (1993) announced their discovery that R 40 is an LBV. This particular case of R 40, characterised by a steady (quasi-linear) behaviour during the phase of light increase, enables us to test the possible objection that the derivation of the underlying pattern of variability of the SD phenomenon is subjective (since it relies on eyeball inspection of and filling in of gaps in complex light curves) thwarted by far more intuition and wishful thinking than should be allowed in any search for periodicities in a not-continuously observed natural phenomenon. Indeed, the steady pace of the star's brightness increase allows us to derive the underlying cyclicities by two independent approaches.

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Table 1. Program star R 40 (P) and comparison Stars (A, B): average $y(V), b-y, m_1, c_1$ and standard deviations σ (in millimag.). N denotes the total number of observations of each star. Note that the results are based solely on data belonging to System 7 Sterken et al. 1993, see also Sterken 1993)

LTPV	HD	MK type	$y(V)$	$b-y$	m_1	c_1	N	σ_y	σ_{b-y}	σ_{m_1}	σ_{c_1}
P5022	6884	A?Ia	10.262	0.171	0.029	0.310	237	166	13	12	112
A5022	6997	G8III	9.090	0.548	0.337	0.260	237	11	8	10	12
B5022	7031	G5	8.565	0.519	0.215	0.325	232	17	7	8	8

Throughout this paper we discuss differential photometry, in the sense that the variability of R 40 is discussed in terms of the differential magnitude of R 40 relative to the corresponding signal for a comparison star in each Strömgren band, and in the Walraven and Johnson V bands.

2. The data

2.1. LTPV $uvby$ photometry, ESO

The $uvby$ data were obtained at ESO in the framework of the "Long-term Photometry of Variables" (LTPV) project which was initiated more than a decade ago (Sterken 1983, 1994). A total of 311 datapoints (i.e. nightly averages of 1–3 measurements) have been collected. Table 1 gives the most important results for each star, as well as the overall averages in $y(V)$, $b-y$, m_1 and c_1, together with the corresponding standard deviations of individual measurements. The data in Table 1 are based on data from "System 7" (see Sterken 1993) only, and they give a general impression of the photometric accuracy of the LTPV programme. The standard deviations of the programme star greatly exceed those of the comparison stars (note that a single strongly-deviating result obtained on JD 2447490.51 for R 40 was not taken into account, as were two other measurements on JD 2446642.94 and 2448429.94). Comparison star A can be regarded as constant, but star B may be a microvariable; both are of later spectral type than R 40 and, consequently, have redder colour indices than R 40 (which, however, is at its reddest near maximum brightness).

The photometric data were published by Manfroid et al. (1991, 1994) and Sterken et al. (1993, 1995), and we refer to these papers for more details on the observing strategy and on the reduction procedure. All our figures are based on data in the instrumental photometric system.

2.2. LTPV Strömgren by photometry, ESO

R 40 has also been observed during a time span of 33 days in October–December 1995, and over 64 days in 1996. The data are, unfortunately, rather sparse, and were collected with the ESO 50 cm telescope in the y and b bands only. A total of 57 new measurements have been obtained by C. Sterken, B. Vos, I. Zegelaar, H. Melief, A. Kelz and M. Storm.

Table 2. Walraven and LTPV V data for R 40 (in magnitudes). $V_{\rm corr}$ is V corrected for the S Dor phase (see text), HJD is Heliocentric Julian Date *minus* 2440000 **[electronic table]**

2.3. $VBLUW$ photometry, ESO

The $VBLUW$ photometry of R 40 was made between 1987 and 1989 with the 90 cm Dutch telescope equipped with the simultaneous $VBLUW$ Walraven photometer. A general description of the monitoring campaign (including the observing strategy and reduction procedures) of luminous and massive stars that included R 40, is given by van Genderen et al. (1985). A total of 85 nightly averages were obtained with a very small mean error of $\sim 0\overset{\mathrm{m}}{.}003$ in V. The sole comparison star used was HD 10747 ($V = 8.17 \pm 0.01$, B3V), a standard star of the Walraven photometric system. The mean systematic difference between the Walraven V and LTPV y magnitudes amounts to $0\overset{\mathrm{m}}{.}001$ with 95% of those data deviating less than $0\overset{\mathrm{m}}{.}003$ from this average. Table 2 gives the Walraven and LTPV equivalent V data, and also the corrected magnitudes $V_{\rm corr}$ that exclude the contribution from the SD phase (see Sect. 4).

2.4. Hipparcos data

132 photometric measurements have been obtained with the Hipparcos photometric instrument (see van Leeuwen et al. 1997). The Hipparcos data, though based on a passband much wider than the Strömgren y band, can be very well combined with our y data by adding $-0\overset{\mathrm{m}}{.}05$ to the H_p magnitudes (see Fig. 1). There is a good agreement with our LTPV data, but the Hipparcos data seem to show a slightly larger scatter. The combined data set provides an almost continuous photometric coverage.

3. The light curves

Fig. 2 clearly shows the gradual increase in visual magnitude V by about $0\overset{\mathrm{m}}{.}07\,\mathrm{y}^{-1}$ with associated reddening in $b-y$, $v-b$ and $u-v$ (the latter amounting to about $0\overset{\mathrm{m}}{.}05\,\mathrm{y}^{-1}$) and cyclic microvariations. The brightening phase is strongly present in y, and decreases towards b and v. Superimposed on these longer-term trends are the microvariations (the so-called α Cygni-type variations near the minimum of the SD cycle, see van Genderen et al. 1997a,b, and the longer [$\sim$ 100 d] cycles near maximum)

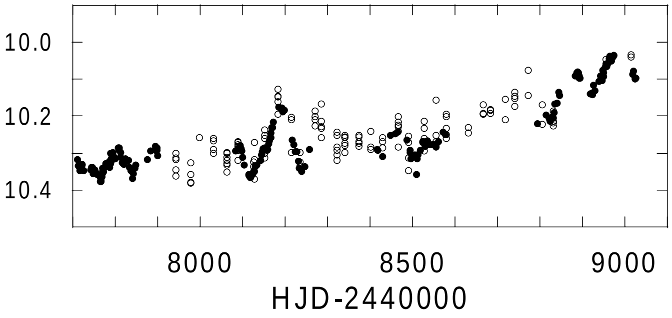

Fig. 1. LTPV y data (•) together with Hipparcos H_p data (○) brought to the same scale

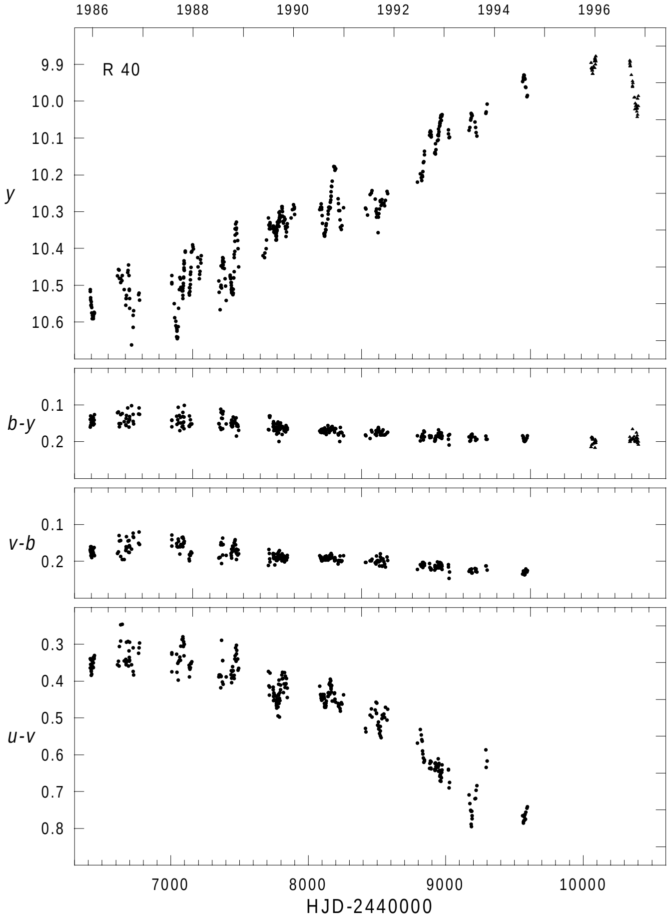

Fig. 2. Differential $y, b-y, v-b, u-v$ light curves of R 40 (P *minus* A) in the instrumental system (•). The top panel also contains the Walraven V magnitudes expressed in the Johnson scale. Filled triangles represent the 1995–1996 LTPV data

and a much slower oscillation about the gradual, brightening trend. The data collected in 1996 show an apparently steep descent in y accompanied by a blueward shift in the $b-y$ colour index. Note that this apparent steep descent could have been enhanced by a coincident descending part of the superimposed variability.

4. Search for periodicities

The new LTPV data are not in the same photometric system as the data described in Sect. 2.1 and are too sparse to be included in a frequency analysis. A period search was thus carried out using Fourier analysis on the differential P *minus* A $y = V$ data in the frequency range 0.0–0.2 cd^{-1}.

The combined V and y light curve was visually inspected, and a hand-drawn continuous enveloping curve was drawn through the minima of the microvariations. The difference between the V magnitude and the corresponding value read from the hand-drawn curve was then subtracted from the observed V, resulting in V_{corr} which describes at each date the microvariations excluding the contribution from the developing SD phase.

In order to assess objectively the approach of eye-estimating the underlying SD variations and correcting the observed V magnitudes for the contribution of the S Dor phase, we have also made a frequency analysis of the $y \equiv V$ magnitudes corrected for a linear trend fitted to all LTPV data of Sect. 2.2 in the y, b and v bands (this trend has a gradient of -0$^{\mathrm{m}}_{.}$069 per year in V).

4.1. Data corrected for the long-term trend by eye-estimate

The spectral window is dominated by a strong peak at 0.00278 cd^{-1}, due to the annual rythm of our observations. The amplitude spectrum shows its strongest peak at $f_1 = 0.010059\,\mathrm{cd}^{-1}$, (a cycle of 99$^{\mathrm{d}}_{.}$4) with weaker peaks on either side at 77$^{\mathrm{d}}_{.}$8 and 139 days. These correspond to a difference in frequency of 0.00278 cd^{-1}, the aliases produced by the annual cycle. A least-squares sine fit with f_1 reduces the $O-C$ standard deviation from 0$^{\mathrm{m}}_{.}$043 to 0$^{\mathrm{m}}_{.}$036, still more than a factor of three larger than the expected s.d. as derived from the differences between the comparison star y measurements. Fig. 3 shows the amplitude spectrum for the $y \equiv V$ data (middle panel) and the corresponding spectral window.

After prewhitening for $f_1 = 0.010059\,\mathrm{cd}^{-1}$, the Fourier analysis yields a number of peaks in the amplitude spectrum where the strongest is $f_2 = 0.00824\,\mathrm{cd}^{-1}$(121$^{\mathrm{d}}_{.}$3, see Fig. 3), corresponding to the semi-period found by Szeifert et al. (1993); the residual remains at a high level $R = 0^{\mathrm{m}}_{.}033$. Further prewhitening with f_2 leads to an amplitude spectrum characterised by very strong noise.

4.2. Data corrected for for the long-term trend by subtracting a linear trend

The strongest peak in the amplitude spectrum appears at 0.01015 cd^{-1}, but a new peak appears at 0.00077 cd^{-1}. We call this frequency f_0; it corresponds to a cycle of $\sim$1300 d. After prewhitening with these two frequencies, the resulting amplitude spectrum shows a maximum at 0.00570 $\mathrm{cd}^{-1}$and a number of peaks of slightly lower power, among which 0.00855 cd^{-1}, a frequency very close to the second frequency found in Sect. 4.1. Most of these peaks are aliases of possible other secondary frequencies (see Fig. 4). Again, prewhitening with any of these

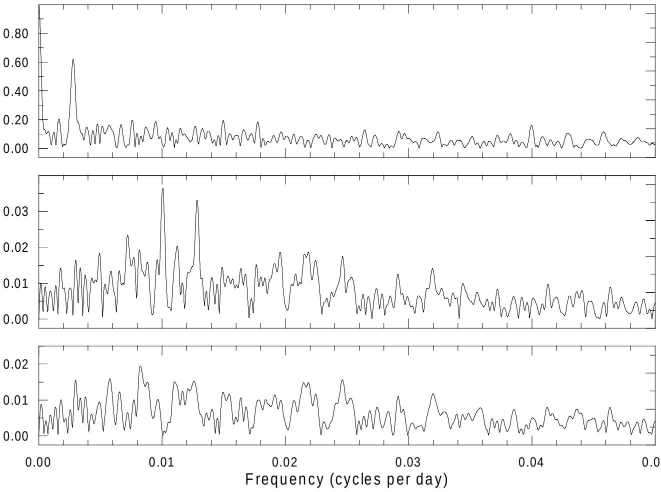

Fig. 3. Spectral window (top) and amplitude spectrum (middle) of R 40 ($V_{\rm corr}$) in the frequency range 0.0–0.05 cd^{-1}. The lower panel is the amplitude spectrum for the $V_{\rm corr}$ data after prewhitening with f_1

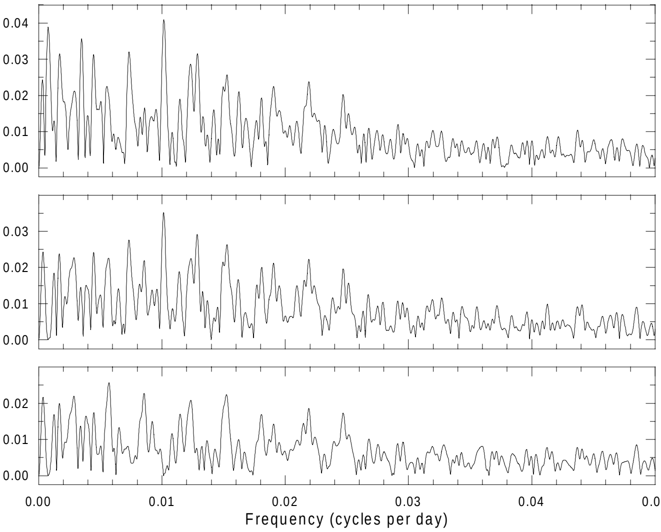

Fig. 4. Top to bottom: amplitude spectrum of the linearly-corrected $y \equiv V$ magnitudes (top), the same after prewhitening for $f_0 = 0.00077$ (middle), and the final amplitude spectrum after prewhitening by the two frequencies f_0 and f_1 (bottom)

frequencies does not convincingly reduce the $O - C$ standard deviation of the fit.

In order to see whether shorter time intervals might reveal significant changes in the amplitude spectra, we divided the data set (corrected for the linear trend) in three more or less equal time intervals, viz. the period before JD2447500 (set 1, 109 points), the time interval between 2447500 and 2448700 (set 2, 127 points) and the remaining data (set 3, 74 points). Each such subset was submitted to a Fourier analysis in the spectral domain below 0.02 cd^{-1}. f_1 is the only frequency that appears with comparable strength in each amplitude spectrum (with amplitude peaks at 0.0102, 0.0105 and 0.0106, respectively for sets 1, 2 and 3), thus lending additional support to our conclusion that the principal cycle of microvariation is visible throughout the ascending branch of the S Dor cycle.

Furthermore, we de-trended all $uvby$ data by removing the linear slope; Fig. 5 is the resulting phase diagram. There we see that the fitted ranges of variation in u and v ($0\overset{\mathrm{m}}{.}090$) are slightly larger than in b and y ($0\overset{\mathrm{m}}{.}085$). In addition, the scatter about the colour curves (see Fig. 2) is very much stronger around 1985 (near minimum SD phase) than several years later. The small difference in y-to-u amplitude and the fact that the amplitude of the colour variations is of the same order as the precision with which the colour can be determined, make it impossible to draw any firm conclusions about the colour behaviour when all data obtained during the ascending SD branch are combined. It should be stressed here that the individual light curves do show a correlation with colour (especially with $u - v$), and that the cycles of 1986–89 also allow a solution with a cycle half as long ($46\overset{\mathrm{d}}{.}2 \sim 2f_1$) with a reversed colour behaviour.

We conclude our frequency analysis by accepting only f_0 and f_1, leaving open the possible presence of secondary frequencies in the microvariations. For the sake of argument, one could adopt f_2, the cycle found by Szeifert et al. (1993), as an acceptable choice for a second frequency. That a second frequency like f_2 could contribute to a better explanation of the complex light curve is shown in Fig. 6 which illustrates the impact of the combination of one slow and two fast cyclic oscillations.

5. Discussion

In Fig. 7 we show the amplitudes resulting from a simultaneous fit of f_0 and f_1 to the linearly-corrrected $uvby$ data. The fitted amplitudes for f_1 show an increase towards the ultraviolet part of the spectrum (but this could be the result of combining the different data sets). f_0, as expected, displays a decreasing amplitude at shorter wavelengths. The colour index behaviour associated with f_0 very distinctly shows that the light maxima in the 1300 d cycle are associated with a reddening, implying that the low-frequency oscillations superimposed on the steady increase in light may be identified with normal SD phases, while the quasi-linear trend may very well be the rising branch of a VLT–SD phase as seen by van Genderen et al. (1997a) in S Dor and AG Car.

At this point we wish to draw the attention to both approaches of de-trending as described in Sects. 4.1 and 4.2. The correction for the rising trend through subtraction of a curve enveloping the magnitude values at light minimum effectively removes all possible low-frequency variation, and assigns the highest spectral power to a cycle length of the order of 100 d (or to one of the alias frequencies). The formal representation of the rising branch by a linear function allows a more objective de-trending, but the forcing of the linear model may, of course, introduce a spurious signal since the rising branch may not be simply linear. However, we find corroboration in long-term light curves of LBVs, viz. AG Car: see Fig. 1 of van Genderen et al. (1997a) where a long sequence of SD phases is superimposed on rather straight stretches of the VLT-SD cycle in the descending branch (carrying maxima 27–30), the quiescent section (supporting maxima 30–35) and the rising part (maxima 35–38).

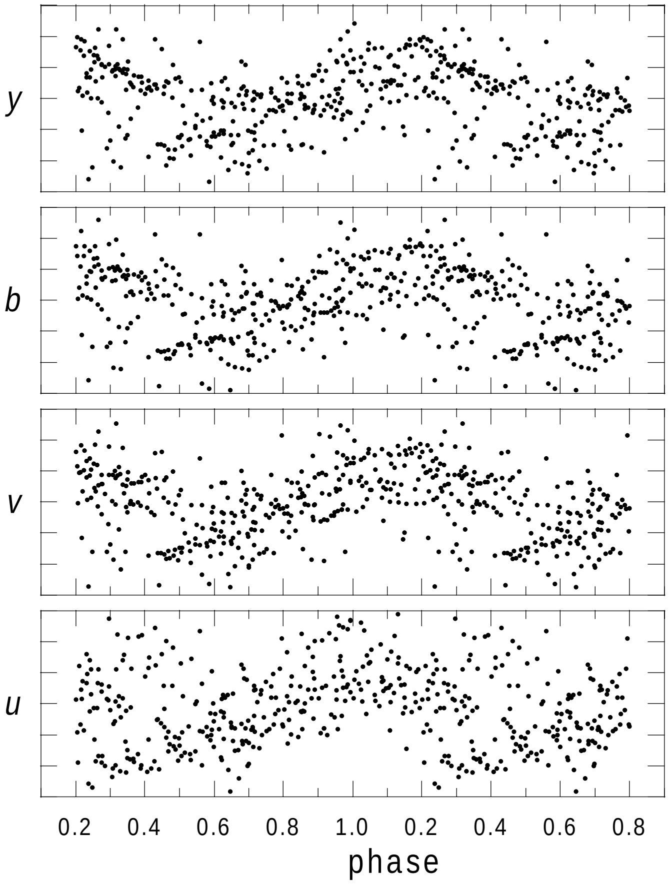

Fig. 5. LTPV $uvby$ magnitudes against phase in the $P = 99\overset{\rm d}{.}4$ period (f_1) covering more than 30 cycles of variation. Phase 0 was chosen arbitrarily, tick marks on the Y-axis are $0\overset{\rm m}{.}05$ apart

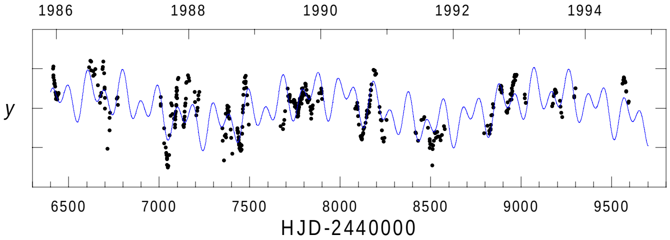

Fig. 6. $y \equiv V$ data corrected for the linear trend underlying the SD phase. The least-squares sine curve was calculated with f_0, f_1 and f_2 (the same frequency as selected by Szeifert et al. 1993). The result of the combination of these three frequencies produces an irregular alternation of the light maxima. Medium and long gaps in the data may, at times, give the impression that the period doubles from one season to the other. Tick marks on Y-axis are $0\overset{\rm m}{.}1$ apart

The SD cycle of AG Car is short ($371\overset{\rm d}{.}4$) and the occurring VLT-SD cycle is slightly longer than 20 y; in the case of R 40, the SD cycle is is three to four times longer (1300 d), with a VLT-SD cycle of the same length as in AG Car, i.e. ~ 20 y. R 40 thus resembles S Dor (SD cycle of 6.8 y and VLT-SD cycle of the order of 40 y, discovered as a result of the very long base line of photometric data).

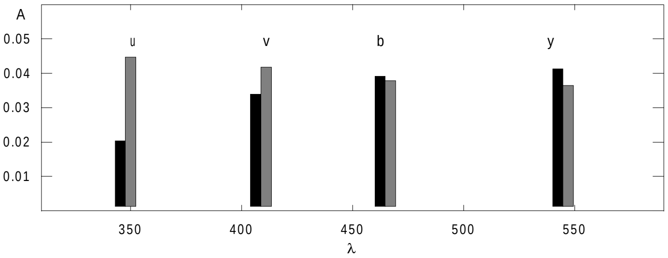

Fig. 7. Amplitudes for the two principal frequencies in function of wavelength of the Strömgren filters. Each group of bars represents, from left to right, the frequencies f_0 and f_1

It is clear that a formal Fourier expression of the light variations with intermediate frequencies does not account for the full variability in all bands, even if a second high-frequency oscillation is taken into account, and this fact is also illustrated in the phase diagrams shown in Fig. 5, where one sees some branches that deviate markedly from the more general light curve. This reflects the well-known fact that the microvariations of LBVs are semi-periodic. The SD and VLT-SD cycles, too, are of somewhat variable length; see the case of AG Car as described by Sterken et al. 1996 and van Genderen et al. 1997a). It is indeed very difficult to distinguish between semi-regular (multi-)cyclic variations and the additional (stochastic) variability that also characterises all luminous stars of these types. What is important is the fact that the microvariations are not irregular, that they are visible during almost the complete duration of the rising VLT-SD branch, and that they have a more or less constant cycle length.

Using $E_{\rm B-V} = 0.14$, Szeifert et al. (1993) derive the following stellar parameters for R 40: $T_{\rm eff}$ = 8700, $log\, g = 0.75, R/R_\odot = 280, L/L\odot = 4.1\,10^5, M_{\rm bol} = -9.4$ at the time of the S Dor maximum in 1991, and $T_{\rm eff}$ = 10000, $log\, g = 0.95, R/R_\odot = 220, L/L\odot = 4.4\,10^5, M_{\rm bol} = -9.5$ at the time of the pre-maximum in 1987. In both cases $M/M_\odot = 16$; it is seen that $M_{\rm bol}$ does not vary through the S Dor variations. The 1991 values for $T_{\rm eff}$ and L applied to Fig. 14 of van Genderen et al. (1992) yield $P = 90^{\rm d}$, in good agreement with our $P_1 = 98\overset{\rm d}{.}4$. Considering the uncertainties on the stellar parameters used, the application of the $P - M - L - T_{\rm eff}$ relation derived by Burki (1978) also yields an acceptable agreement, $P = 110^{\rm d}$.

Though pulsation models are not available for stars that are not purely periodic, we did calculate the pulsation constant $Q = P(\rho)^{1/2}$ using the above parameters, and obtained $Q = 0.08$ for P_1 with stellar parameters for the SD maximum, and $Q = 0.12$ in the time interval preceding the phase of SD maximum.

Lovy et al. (1984) calculated the (radial) pulsation properties of stars with $M > 15 M_\odot$ for the radial fundamental mode (P_0) and the first and second overtones, but none of their models exactly fits the stellar parameters of R 40. Model 302 ($T_{\rm eff} = 3.90, \log R/R_\odot = 2.439, M/M_\odot = 24.6$, and $M_{\rm bol} = -8.76$) corresponds to R 40 in its bright and cool phase, and yields $P_0 = 42\overset{\rm d}{.}8$, very close to $46\overset{\rm d}{.}2 \sim 2f_1$ with $Q = 0.047$, twice as large as the radial-pulsator Q values derived by these authors.

The star, at its hottest phase (1986–87), reached $T_{\rm eff}=10\,000$, so that from Eq. 2 of Lovy et al. (1984) it follows that $P\sim 30$ d is the shortest radial-pulsator period to be expected. We did not find oscillations of such short cycle length, which adds evidence to the conjecture that R 40 might not be a radial pulsator. Nor does the 1986–89 observed dominant oscillation (cycle length ~ 46 d) lead to a Q value that is acceptable for radial pulsation.

Our multicolour photometry, in fact, provides observables that could be useful to discriminate between radial and non-radial modes and may even yield unambiguous l-values provided suitable models for the gravity and temperature range of R 40 would exist. Watson (1988) derived diagrams of relative colour-to-visual amplitude versus colour-minus-visual phase differences ($A_{\rm B-V}/A_{\rm V}$ and $\phi_{\rm B-V}-\phi_{\rm V}$) as a function of l. Apart from l, the points in such a diagram, naturally, depend on the equilibrium parameters of the star. Our data provide for f_1: $A_{\rm u-y}/A_{\rm y}=0.59$ and $\phi_{\rm u-y}-\phi_{\rm y}=0.17({\rm rad})=10^\circ$. A straightforward application of our observables (even if transformed to the UBV system) to Watson's diagrams is not permitted because the parameter space used in these diagrams is incompatible with ranges occupied by LBVs. Moreover, these observables are sensitive to the metal content parameter (Z), another obstacle when dealing with stars in the SMC. Our data should allow more precise assessment of the pulsation mode(s) of R 40 as soon as proper phase-amplitude diagrams become available.

6. Conclusions

We have shown that the light variations of R 40 look very much like those seen in other α Cygni variables and LBVs (at minimum and maximum phase, see van Genderen et al. 1997a,b), another indication that, most likely, all such stars exhibit multiperiodic light variability.

We find evidence that the light variability of R 40 can be separated on the basis of at least 2 frequencies superimposed on a linear trend between JD 2446300 and 2449400. The longest cycle ($\sim$ 1300 d) represents the SD oscillation (see van Genderen et al. 1997a,b), the shorter cycles describe the microvariations. Note that also for ζ^1 Sco such a long cycle of oscillation was found, and that the latter very likely corresponds to an SD phase as well (Sterken et al. 1997). A strong residual scatter remains; as in ζ^1 Sco it is the stochastic component of the light variation.

Our work indicates that R 40 provides a direct demonstration (based on contemporaneous highly-accurate data) that the so-called normal SD cycle ($\sim$ 1300 d) does exist, and that the present bright state is a VLT-SD phase.

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