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Photometric variability of the SMC W-R binary HD 5980*

C. Sterken[1,**] **and J. Breysacher**[2]

[1] University of Brussels (VUB), Pleinlaan 2, B-1050 Brussels, Belgium
[2] European Southern Observatory, Karl-Schwarzschildstrasse 2, D-85748 Garching, Germany

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Abstract. We present the results of a photometric monitoring campaign of the W-R binary HD 5980 conducted in November–December 1995, 16 months after the LBV-like outburst of one of the components of the system. On the basis of almost 800 y-band measurements, an improved orbital ephemeris is derived. We also report the discovery of a coherent 6 h periodic oscillation visible in the Strömgren b and y bands with amplitudes $\sim 0\overset{\mathrm{m}}{.}025$. This short period may be related to pulsations of the primary or secondary component.

Key words: binaries: eclipsing – stars: oscillations – stars: Wolf-Rayet – stars: individual: HD 5980

1. Introduction

HD 5980 is the brightest Wolf-Rayet binary star in the SMC. The eclipsing character of the star, which is associated with the luminous young cluster NGC 346, was discovered by Hoffmann et al. (1978) and the correct orbital period, $P = 19\overset{\mathrm{d}}{.}266$ was found by Breysacher & Perrier (1980). A subsequent detailed light curve analysis of the system (Breysacher & Perrier 1991) confirmed the strong eccentricity of the orbit ($e = 0.324$) and gave evidence for the existence of a third unresolved component in the line of sight, possibly observed by Massey et al. (1989). Until HD 5980 was claimed to be a WN4.5+WN3 pair, plus a probable line-of-sight OB-type neighbour (Niemela 1988), the object has been consistently classified as a binary of the WN3-4+OB type (cf. Breysacher et al. 1982).

Spectacular and sudden spectral changes were registered between 1993 and 1995, both in the optical (Barbá & Niemela 1995, Barbá et al. 1995) and in the UV region (Koenigsberger et al. 1995), when HD 5980 suffered an LBV-like outburst. The system brightened by about three visual magnitudes in July–August 1994, and became then one of the brightest stars of the SMC ($V = 8.6$, Bateson & Jones 1994), showing a spectrum similar to the η Car-type variables, with strong He I and Balmer H P Cygni lines (Barbá et al. 1995). For a review of the star's photometric and spectrographic history, see Breysacher (1997). One aspect of HD 5980's nature, however, has never been thoroughly investigated: the possible presence of short-period continuum variations, notably periodic variations of pulsational type.

The present paper presents the results of photoelectric photometry at high time resolution of this enigmatic object.

2. The photometric data

Intensive observing over one full orbital period was carried out by one of us (CS) in November–December 1995 at the La Silla Observatory, and this programme was complemented by further measurements carried out in the framework of the "Long-Term Photometry of Variables" project (Sterken 1993, 1994). The combination of both data sets yielded about 750 Strömgren b and y measurements. The complete data set contains 21 nearly contiguous nights with data taken at a time resolution of about 12 minutes.

We used the ESO 50 cm telescope equipped with a sequential photometer using an uncooled EMI 9789QA photomultiplier and a set of Strömgren b and y filters. All our measurements were made differentially with respect to HD 5572 (F5V), the same comparison star as used by Hoffmann et al. (1978) and Breysacher & Perrier (1980). Sequences of 10-second integrations for 2–4 minutes assured equivalent photon statistics for program and comparison star in both filters. Since the sky background amounts to 20–40% of the total signal, the reduction procedure was very tedious and involved close inspection of the sky measurements for each star. Fig. 1 shows the $y \equiv V$ differential magnitude and colour index $b - y$ for all our Strömgren data.

In addition, 38 Geneva $UBVB_1B_2V_1G$ measurements of HD 5980 and the comparison star were obtained at the Swiss 70 cm telescope which is operated on La Silla by the Geneva Observatory. All our data will be published *in extenso* by Sterken et al. (1997a). In order to calibrate the Geneva and Strömgren visual (V, y) magnitudes to a common scale, we sampled all y

Send offprint requests to: C. Sterken

* Based on observations obtained at the European Southern Observatory at La Silla, Chile (observing proposals ESO 56-D0392 and 56-D0249).

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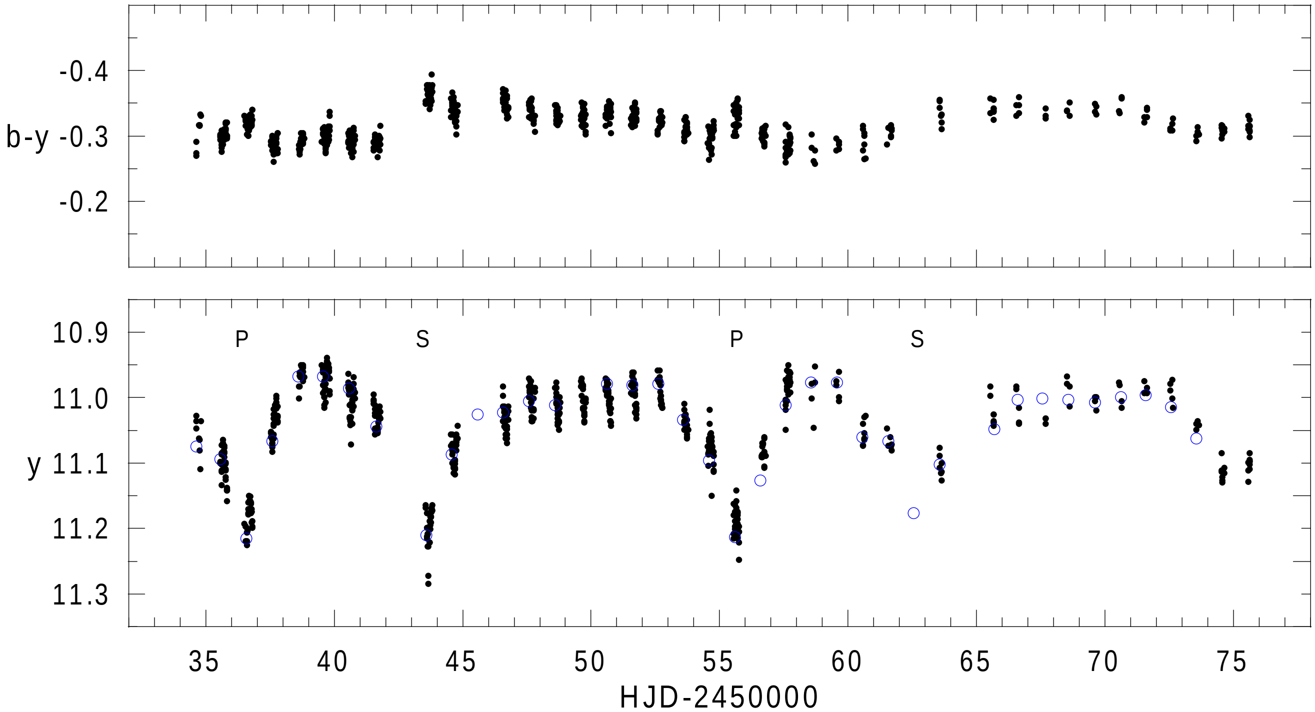

Fig. 1. y orbital light curve and $b-y$ colour index variations for HD 5980. The • refer to the observations carried out at the ESO 50 cm telescope, the ○ correspond to the y magnitudes derived from the measurements in the Geneva photometric system. The b and y data being in the instrumental system, the labeling on the Y-axis is only approximate. P and S indicate, respectively, primary and secondary eclipses

magnitudes obtained within ±30 minutes from a Geneva measurement. 25 such occurrences were found, and the average differential magnitude $y - V_{\rm Geneva} = -0\overset{\rm m}{.}046 \pm 0\overset{\rm m}{.}002$. The resulting visual magnitude is also plotted in Fig. 1, where • represent the ESO y data and ○ the Geneva-V magnitudes. At the time of primary and secondary eclipse, the system is visibly bluer than during the out-of-eclipse phases. The existence of such a colour effect at primary minimum was already noticed by Breysacher & Perrier (1980).

3. Eclipses and orbital period

The primary-eclipse ephemeris given by Breysacher & Perrier (1980) is $\mathrm{HJD_{min}} = 244\,3158.771 + 19.266\,E$, the period being accurate within $0\overset{\rm d}{.}003$. Since then, more than 350 cycles have elapsed, bringing the formal uncertainty on predicted primary eclipse time to almost one day in 1995. Our new data should, in the first place, assure improvement of the ephemeris.

We have not applied a straightforward period search programme, but we preferred to recur to the classic linear-ephemeris method, using the equation given above as a first approximation. In doing so, one should not forget that the times of minimum light given in the literature are not necessarily the moments of the real minimum, but are in most cases close to (before or after) the real event (as is also the case for some of our own data).

We performed the analysis for primary as well as for secondary eclipses. Table 1 of Hoffmann et al. (1978) gives one time of primary minimum, and three times of secondary minimum (note that they listed JD 243 8920.25 as a primary minimum though it is, in fact, a secondary minimum). The Breysacher & Perrier (1980) data contain three primary and three secondary minima, and the data given by Seggewiss et al. (1991) list one primary and one secondary minimum. Our own data yield four near-primary minima and two secondary times of minimum (see Table 1).

Table 1. Overview of all available times of (near-) minimum light of HD 5980. The references are HA: Hoffmann et al. (1978), BP: Breysacher & Perrier (1980), SA: Seggewiss et al. (1991), SB: this work

Primary $T_{\rm min}$			Secondary $T_{\rm min}$		
HJD	E	ref	HJD	E	ref
2443216.52	3	HA	2438927.5	-220	HA
2444102.865	49	BP	2443165.578	0	HA
2444121.735	50	BP	2443242.53	4	HA
2444160.670	52	BP	2444070.89	47	BP
2447454.717	223	SA	2444148.698	51	BP
2450036.61	357	SB	2444167.584	52	BP
2450055.56	358	SB	2447442.578	222	SA
2450094.59	360	SB	2450043.66	357	SB
			2450062.56	358	SB

Separate analysis of the primary and secondary minima yields, resp. $P = 19\overset{\rm d}{.}2656$ and $19\overset{\rm d}{.}2653$, with a difference in zero

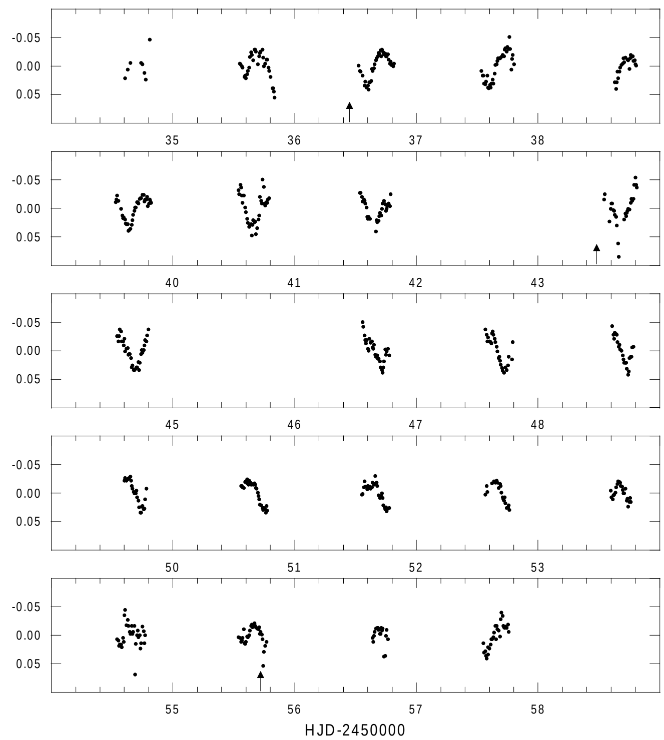

Fig. 2. b microvariations (de-trended for the average orbital light curve). Tick marks on the Y-axis are $0\overset{m}{.}05$ apart. Vertical arrows indicate the times of primary or secondary eclipse as derived from Eq. (1)

epoch amounting to $7\overset{d}{.}024$, involving a phase difference 0.365, in agreement with Breysacher & Perrier (1980) and Seggewiss et al. (1991) who found 0.36. Then, we merged both sets by advancing all times of secondary minimum with $7\overset{d}{.}024$ and thus acquired an extra number of times of pseudo-primary minimum. The resulting ephemeris (including the Hoffmann et al. (1978) secondary minimum at $E = -220$) becomes

$$\mathrm{HJD}_{\mathrm{min}} = \underset{\pm 0.07}{2443158.705} + \underset{\pm 0.0002}{19.2654}\,E \qquad (1)$$

thus an improvement by a factor of 10 on the accuracy of the orbital period. The $O - C$ differences amount to $\pm 0\overset{d}{.}3$ (these deviations are due to the inherent uncertainties of estimating the real times of minimum, and are of the same order as in the Breysacher & Perrier 1980 data).

The shape of the new light curve at mean light level, i.e. after removal of the microvariations (cf. Breysacher 1997), has changed as compared to the one reported by Breysacher & Perrier (1991). The primary minimum is much broader and asymmetrical, the secondary minimum shows more extended “wings”. The curve has now a rounded form between the primary and the secondary eclipse. A detailed discussion of these changes will be given in a dedicated light curve analysis.

4. Microvariations

A glance at Fig. 1 reveals variability on a short time scale.

We have attempted to study in detail the microvariations obtained during the dedicated observing mission (i.e. all data collected before JD 2450058). First we removed the contribution of the orbital light curve by subtraction, night by night, of the nightly average in y or b. The resulting “de-trended” light curve is shown (for b) in Fig. 2: it seems that the microvariations are present on most nights, even near the eclipses (see vertical arrows in Fig. 2). It is also obvious that the amplitude of the microvariation is variable on a night-to-night time scale.

Though almost all photometric data reported in the literature have been taken at time resolutions that are inadequate for revealing high-frequency variations, the data of Seggewiss et al. (1991) do contain several data strings that show significant variability (over $0\overset{m}{.}05$–$0\overset{m}{.}06$) on a time scale of hours. More specifically, the five Strömgren b magnitudes collected on JD 2447442—a secondary-eclipse night—display a wavy pattern on a frequency of about 5 $\mathrm{c\,d}^{-1}$ and a peak-to-peak amplitude of $0\overset{m}{.}065$, thus supporting the possibility that the short period oscillation might be stable over many years. We remind that both the frequency and the amplitude derived from the Seggewiss et al. (1991) data are very uncertain because they were derived from only five data points collected over a time span of six hours.

As the comparison star is of a later spectral type than HD 5980, one might be tempted to ascribe the reported variations to atmospheric colour effects. We have very carefully checked this aspect, and must refute this possibility on the following grounds:

- the variations are visible in the non-differential measurements of the HD 5980, whereas they are not seen in the y and b magnitudes of the comparison star
- extinction coefficients were determined on the basis of our own data, and relying on the extinction coefficients provided by the Geneva observers. No acceptable set of extinction coefficients could be found that would render the program star constant
- though on many nights we observed at large hour angles on both sides of the meridian, the times of maximum light do not correspond to the times of meridian passage
- the air mass ranged from $X = 1.36$ to $X = 2.05$, but the average differential air mass is 0.008, and ΔX never exceeds 0.04 (95% of the differential air mass values are below 0.03). Even with an error of more than 100% on the extinction coefficient, the resulting photometric error will remain under the photon shot noise error
- the fact that HD 5980 has emission lines in the spectral region occupied by our pass bands cannot account for the variability: Fig. 1 of Barbá et al. (1995) vividly shows that the He I line at 471 nm is present with moderate strength; the strong He II line at 541 nm in the y band may be responsible for some of the enhanced scatter seen in y relatively to b, but can in no way account for all the variability seen in Fig. 2.

The procedure of de-trending the light curve yields about 620 datapoints in y and b, and these were submitted to a Fourier analysis in the frequency range 0–10 $\mathrm{c\,d}^{-1}$. The spectral window does not reveal much structure besides the dominating strong peaks at 1 $\mathrm{c\,d}^{-1}$ intervals. The amplitude spectra in y show the

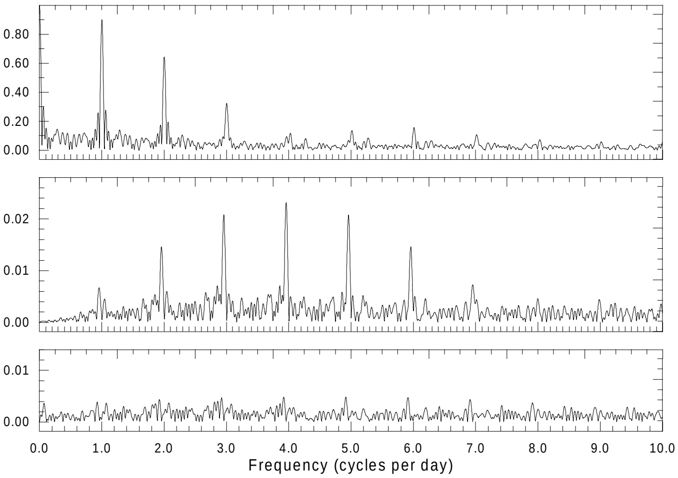

Fig. 3. Amplitude spectrum (middle) and spectral window (top) for the b data. The lowest panel is the amplitue spectrum for the b data prewhitened for f = 3.9580

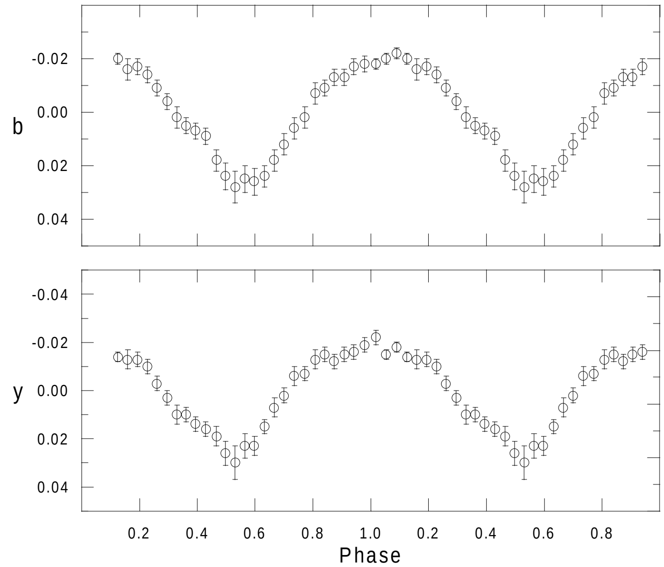

Fig. 4. Phase diagram for the de-trended y and b data. Phase bins correspond to about 12 minutes, the typical time resolution of our data; the epoch is arbitrary

highest peak at 3.9570cd^{-1}, with several 1 cd^{-1}aliases, some of which are rather strong (Fig. 3 shows the results of the Fourier analysis for the b data). Similarly, the b amplitude spectrum shows the same pattern and yields a best frequency 3.9591 cd^{-1}, thus a period of 6.06 hours (6h 04m). The peak-to-peak amplitude of the least-squares sine wave is $0^{\rm m}_{.}048$ in b, and $0^{\rm m}_{.}044$ in y. The residual noise yields a dispersion σ = $0^{\rm m}_{.}014$ in y and $0^{\rm m}_{.}012$ in b, an improvement over the original scatter by about a factor $\sim$ 1.5, but still a factor of almost two higher than the estimated observational scatter. We have prewhitened the de-trended b and y data, but could not identify any possible additional frequencies or harmonics, as can be seen in the lower panel of Fig. 3. We stress, though, that it is possible that not f_1 = 3.958 is the physical frequency, but that one of its 1 cd^{-1}aliases might be the real frequency. As is well known, only multi-site observations can help to resolve this ambiguity.

Fig. 4 is the phase diagram for the 6.06 h (3.9580cd^{-1}) regular oscillations (the epoch was arbitrarily set to JD 2450034.06, and the bin size is 0.033 and corresponds to the typical time resolution of the measurements).

5. Discussion

Antokhin et al. (1995) investigated the photometric variability of five W-R stars. In four of them, they found no traces of coherent periodic high-frequency variability, but in one case (WR 66) they found a clear periodicity of 3.5 hours that is stable over at least 4 years. The least-squares sine-wave amplitude in the Johnson V band was $0^{\rm m}_{.}021$, very similar to the amplitude found in the HD 5980 y and b data. Besides the variability on a time scale of hours, the light variation of HD 5980 resembles the case of WR 66 in yet another aspect, viz. the presence of some stochastic variability, as can be seen in the light curve and also in the magnitude of the residual scatter discussed in Sect. 4. Such kind of stochastic variability seems to be common in massive stars, see for example the case of ζ^1 Sco, a candidate LBV (Sterken et al. 1997b).

A possible scenario to explain the nature of the short-period variability could be binarity of one of the components. With $M_1 \sim$ 27–38$M\odot$ and $M_2 \sim$ 6–18$M\odot$ (Moffat 1997), an additional companion with a revolution time of 3–5 cd^{-1}(including the nearest aliases to f_1) would have an orbit with a semi-major axis between 6 and 8 $R\odot$, a situation that—as was also pointed out by Antokhin et al. (1995)—might resemble the configuration as seen in the massive X-ray binary Cyg X-3, except for the absence of evidence that the HD 5980 system (alike WR 66) is an X-ray emitter (as concluded from the extensive X-ray study of the SMC by Wang & Wu 1992 who obtain a statistical 3σ upper limit to the X-ray luminosity per SMC W-R star of 2×10^{34} erg s^{-1}, which is not quite beyond the range for Galactic W-R stars). The binary explanation would also not account for the fact that the short-period oscillations remain visible during eclipses (our data and the evidence based on Seggewiss et al. 1991), and such a peculiar triple system would very unlikely be a stable configuration.

As Antokhin et al. (1995) point out, the critical rotation period of a typical WN star is of the order of days, and thus much too long to attribute the microvariations to ultra-short period rotation of the most massive component. With the lower limit for the mass of the secondary (6 $M\odot$) and a core radius of $\sim 3R\odot$, the critical rotation period would be $P_{\rm crit}$ = $0^{\rm d}_{.}25$, so one might be able to somehow associate the regular microvariations with a rotating spotted secondary, though such an explanation remains in conflict with the fact that the microvariations seem to persist during eclipse phases.

The alternative explanation is one in terms of radial or non-radial pulsations. At this point, we wish to draw the attention to the fact that if the WR character of HD 5980 had not been established before, and if the star had not been verified to be a member of the SMC, its light curve as shown in Fig. 2 would make up enough ground to believe that we are dealing with β Cephei-type variability. The 6.06 h period is indeed compatible with observed pulsation periods of β Cephei stars (10% of the β Cephei stars listed in Table 1 of Sterken & Jerzykiewicz 1993 have periods of 6 h and longer), as is the small amplitude of variation. Moreover, some β Cephei stars pulsate with only one frequency, and the mass range of the companion (6–18$M\odot$) is compatible with the masses of the heaviest β Cephei stars (see Fig. 20 in Sterken & Jerzykiewicz 1993).

There are two arguments against the β Cephei star hypothesis. First, the Strömgren β index (β = 2.50) is rather extreme when compared to the indices of the galactic field stars (Fig. 7 of Sterken & Jerzykiewicz 1993). However, the measured β index must be strongly contaminated by the emission in the Hβ line, as can be inferred from the calculated β index (Cramer 1994) based on the Geneva photometry: $\beta_{\rm calc} = 2.638 \pm 0.001$, a value that meets no difficulties representing a β Cephei star, though rather representative for a less-massive star than is the case here.

The second argument is that the pulsation mechanism in β Cephei stars is an iron opacity mechanism and thus implies a heavy-element dependence (see, for example, Gautschy & Saio 1993, Dziembowski & Pamyatnykh 1994, Pamyatnykh 1997), a fact that is directly supported by Balona (1992) who surveyed NGC 330 in the SMC and could not find any β Cephei stars. The fact that HD 5980 appears near the Eddington limit (Barbá et al. 1995) and that the regular oscillation seems to persist through the eclipse phases are additional constraints limiting this path of thought.

Noels & Scuflaire (1986) concluded that in a mass-losing massive star in the H-burning shell phase vibrational instability may be triggered during a short time (a few thousand years). The observed period of 6.06 h, in conjunction with the mass range as given by Moffat (1997), could possibly correspond to one of the models given by Noels & Scuflaire (1986).

Our multicolour photometry, in principle, contains information about the pulsation mode because the light amplitudes and phases in different bands depend on the temperature and gravity variations. Watson (1988) derived diagrams of relative colour-to-visual amplitude versus visual phase differences (actually, $A_{\rm B-V}/A_{\rm V}$ and $\phi_{\rm B-V} - \phi_{\rm V}$) that could help identify radial or non-radial pulsation processes. Unfortunately, the procedure of separating the intrinsic high-frequency variability from the orbital light variations leaves room for doubt so that the ratios that we obtain from our data (viz. $A_{\rm b-y}/A_{\rm y} = 0.36$, $\phi_{\rm b-y} - \phi_{\rm y} = -14^\circ$) are not dependable enough to make possible a solid identification. Observing the microvariations at shorter wave lengths (e.g. in u) would be very useful in this respect.

6. Conclusions

The photometric monitoring of HD 5980 reported in the present paper has contributed to significantly improve the orbital period and ephemeris of this very interesting massive binary. The most important new element emanating from this campaign is the discovery of the coherent 6.06 h period in the light of the b and y bands. The fitted amplitude in b is of the same order as the fitted y amplitude, but the observed amplitude is somewhat larger in b than in y. Whether this pulsation is due to the WR star or due to its companion, or to a third body (a possible β Cephei star?), or even comes from wind collisions, is to be seen.

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References

Antokhin I., Bertrand J.-F., Lamontagne R., et al. 1995, AJ 817
Balona L.A., 1992, MNRAS 256, 425
Barbá R.H., Niemela V.S., Baume G., Vazquez R.A. 1995, ApJ 446, L23
Barbá R., Niemela V., 1995, IAU Symp. No. 163, p. 254
Bateson F.M., Jones A.F. 1994, Publ. Var. Star Section RASNZ, No. 19
Breysacher J., Perrier C., 1980, A&A 90, 207
Breysacher J., Perrier C., 1991, IAU Symp. No. 143, 229
Breysacher J., Moffat A.F.J., Niemela V.S., 1982, ApJ 257, 116
Breysacher J., 1997, in *Luminous Blue Variables: Massive Stars in Transition*, Eds. A. Nota et al., 1997 in press
Cramer N., 1994, *Applications de la photométrie de Genève aux étoiles B et à l'extinction interstellaire*, Thèse 2692, Université de Genève
Dziembowski W.A., Pamyatnykh A.A., 1993, MNRAS 262, 204
Gautschy A., Saio H., 1993, MNRAS 262, 213
Hoffmann M., Stift M.J., Moffat A.F.J., 1978, PASP 90, 101
Koenigsberger G., Guinan E., Auer L., Georgiev L. 1995, ApJ 452, L107
Massey P., Parker J.W., Garmany C.D. 1989, AJ 98, 1305
Moffat A.F.J., 1997, personal communication
Niemela V., 1988, in *Progress and Opportunities in Southern Hemisphere Optical Astronomy*, V.M. Blanco & M.M. Phillips (eds.), A.S.P. Conf. Series, 1, 381
Noels A., Scuflaire R., 1986, A&A 161, 125
Pamyatnykh A.A., 1997, in *A Half Century of Stellar Pulsation Interpretations*, PASP Conf. Ser., in press
Seggewiss W., Moffat A.F.J., Lamontagne R., 1991, A&AS 89, 105
Sterken C. 1993, in *Precision Photometry*, D. Kilkenny, E. Lastovica, J. Menzies (Eds.), South African Astronomical Observatory, 57
Sterken C. 1994, in *The Impact of Long-Term Monitoring on Variable-Star Research*, NATO ARW, Eds. C. Sterken, M. de Groot, NATO ASI Series C, 436, 1, Kluwer Academic Publishers
Sterken C., Jerzykiewicz M., 1993, Space Sci. Rev. 62, 95
Sterken C., Vos B., Zegelaar I. et al. 1997a, JAD, in preparation
Sterken C., de Groot, M., van Genderen A.M., 1997b, A&A in press
Wang Qingde, Wu Xiaoyi, 1992, ApJS 78, 391
Watson, R.D. 1988, ApSS 140, 255