A&A 373, 960–965 (2001)
DOI: 10.1051/0004-6361:20010641

Astronomy & Astrophysics

HD 169981 – an overlooked photometric binary?⋆

H. Lehmann[1], G. Hildebrandt[2], K. P. Panov[3], and G. Scholz[2]

[1] Thüringer Landessternwarte Tautenburg, Karl-Schwarzschild-Observatorium, 07778 Tautenburg, Germany
e-mail: lehm@tls-tautenburg.de
[2] Astrophysikalisches Institut Potsdam, An der Sternwarte 16, 14483 Potsdam, Germany
e-mail: ghildebrandt@aip.de
[3] Institute of Astronomy, Bulgarian Academy of Sciences, Sofia, Bulgaria
e-mail: kpanov@astro.bas.bg

Received 30 January 2001 / Accepted 2 May 2001

Abstract. In 1999 and 2000 we obtained spectroscopic and photometric observations of the A-type binary star HD 169981. The observations were part of a campaign to search for short-term photometric and radial-velocity variations among early-type binaries. From the radial velocities of 18 metal lines we derived more precise orbital elements. Quite unexpectedly, our photometric data show a dip that could be caused by an eclipse. The same feature is also visible in the Hipparcos data. From our analysis of the available observations we have estimated the physical parameters of the binary. Neither the spectroscopic nor the photometric observations hint at any short-term variations.

Key words. stars: binaries: eclipsing – stars: binaries: spectroscopic – stars: individual: HD 169981

1. Introduction

HD 169981 (HR 6917, GC 25165, Boss 4669, HIP 90342) was announced in 1918 as showing variable radial velocity (hereinafter RV), and spectroscopic orbital elements were first derived by Young (1919). No further efforts appear to have been made to refine the orbital parameters. Young gave the following elements: $P = 9.6120 \pm 0.0004$ d, $e = 0.4684 \pm 0.0083$, $K = 28.49 \pm 0.37$ km s^{-1}, $\omega = 326\overset{\circ}{.}43 \pm 0\overset{\circ}{.}85$, $\gamma = 7.54 \pm 0.23$ km s^{-1}, and $f(M) = 0.016\ M_{\odot}$, where P is the period, e the eccentricity, K the semi-amplitude, ω the longitude of periastron, γ the system velocity, and $f(M)$ the mass function.

According to Abt & Morrell (1995), the spectral/luminosity class of the visible star is A2 III and the projected rotational velocity, $v \sin i$, is 10 km s^{-1}. Rufener & Bartholdi (1982) mentioned that the star shows small brightness variations, but gave no details.

In the present paper we summarize the results of an investigation to study the binary nature of HD 169981 and to look for short-term RV and photometric variations.

Send offprint requests to: G. Scholz,
e-mail: gscholz@aip.de

⋆ Based on spectroscopic observations made with the 2-m telescope at the Thüringer Landessternwarte Tautenburg, Germany, and photometric observations made with the 0.6-m telescope of the National Astronomical Observatory Rozhen, Bulgaria.

2. Observations and reductions

384 CCD spectrograms of HD 169981 were obtained in 1999 and 2000 with the coudé échelle spectrograph of the 2-m telescope of the Thüringer Landessternwarte Tautenburg (hereinafter TLS) by one of us (H.L.). Throughout, the time sampling was 5 min, allowing 4-min exposures for each spectrogram. The spectrograms have a two-pixel resolution of 37 000 and a mean S/N ratio $\gtrsim$250. The spectrograms were reduced with a modified MIDAS procedure. For the wavelength calibration we used a Th-Ar lamp, and determined the RV zero-point from of a large set of telluric lines. The RVs were derived from 18 metal lines between Hα and Hβ that included 6 lines of Fe I, 7 of Fe II, 1 of Cr I, 1 of Ti II, 1 of Mg I and 2 of Si II. The RVs derived from the various chemical elements showed no differences, so we averaged the values for each spectrogram.

The photometric observations were carried out with the 60-cm cassegrain telescope of the Bulgarian Astronomical National Observatory at Rozhen. The computer-controlled photometer is equipped with an EMI 9789QB multiplier, a set of filters which correspond to the *ubv* color system and a diaphragm of 28″. The integration time was ten seconds per measurement and filter. Reductions included the corrections for dead-time, background, differential extinction, and the correction of the data to the standard UBV system. The observations

Table 1. Journal of the observations of HD 169981.

Observations	JD 2410000+	N_r	N_n
spectroscopy			
Young's data			
Mt. Wilson/Ottawa	9913−11501	-	8
Victoria	11769−12154	-	31
new data			
CCD TLS	41367−41818	8	384
photometry			
Hipparcos	37900−39053	41	155
Rozhen	41367−41818	29	849

of HD 169981 included the comparison star HD 168913 and the check star HD 168914.

The logs of the observations are summarized in Table 1. N_r denotes the number of runs and N_n the number of spectrograms or the number of photometric measurements, respectively. JD is the heliocentric Julian Date.

3. Orbital variations

For the orbital calculation we used the method of differential corrections after Schlesinger (1908). Solutions I and II of Table 2 list the orbital elements derived from the RVs noted in Young's paper. Solution I includes only the Victoria RVs and solution II includes the Victoria, Mt. Wilson, and Ottawa RVs, respectively. Comparing with Young's elements of 1919, mentioned in Sect. 1 of the present paper, the results are in good agreement with each other. But, we have to consider that Young derived his elements alone from the RVs obtained at Victoria, whereas he included all RVs for the determination of the orbital period, i.e., the RVs from Mt. Wilson, Ottawa, and Victoria.

Solution III gives the orbital elements derived from the TLS RVs. The rms is smaller by a factor of about ten and reflects the much higher accuracy of our CCD spectra. Because we carried out our calibration of the instrumental RV zero point on the telluric lines – this procedure has been tested on various RV standard stars – we can assume that our RVs are on the IAU velocity standard. The agreement of the γ-velocities of solution I and III is quite well though we account the result to be more or less fortuitous, however. Within the measuring accuracy there exists also a good agreement of most of the other orbital elements. Only the period and the time of periastron passage are outside of the accuracy range.

To use the large time basis between the data sets we combined the 39 photgraphic RVs given by Young and the values of our 384 CCD spectrograms. For the investigation we correct Young's RVs according to the derived difference in the γ-velocity and weight the data according to the observed rms ratio. So our data get a weighting factor of 100 compared to a weighting factor of 1 for Young's RVs. Owing to the extreme weighting scheme we do not expect to get any more accurate information on the orbital elements except for the period P and for the time of periastron passage T, for which the larger time basis plays a crucial role. The result is listed in the orbital solution IV of Table 2. Here all elements but P and T have been fixed to the values of solution III.

Table 2. Orbital elements for HD 169981 for single and combined data sets. In parenthesis we give the deviation from the combined solution IV in units of 1 σ of the individual solution. Epochs of eclipses are listed at the bottom, where ϕ is the position in the orbital curve.

Solution I, Victoria RVs				
P [d]	9.6163	±	0.0014	(3.6)
$T_{periastron}$	2438776.5	±	2.5	(1.7)
K [km s^{-1}]	28.2	±	0.61	(0.1)
e	0.467	±	0.016	(0.7)
ω [deg]	326.9	±	2.3	(1.0)
γ [km s^{-1}]	7.55	±	0.32	
rms [km s^{-1}]	1.75			
Solution II, Mt. Wilson, Ottawa, Victoria RVs				
P [d]	9.61185	±	0.00035	(1.7)
$T_{periastron}$	2438773.36	±	0.61	(1.7)
K [km s^{-1}]	28.44	±	0.71	(0.4)
e	0.458	±	0.017	(0.2)
ω [deg]	328.2	±	2.8	(0.3)
γ [km s^{-1}]	7.73	±	0.39	
rms [km s^{-1}]	2.34			
Solution III, TLS RVs				
P [d]	9.61192	±	0.00013	(5.1)
$T_{periastron}$	2438771.43	±	0.18	(5.0)
K [km s^{-1}]	28.146	±	0.017	
e	0.45510	±	0.00069	
ω [deg]	329.09	±	0.15	
γ [km s^{-1}]	8.596	±	0.022	
rms [km s^{-1}]	0.23			
Solution IV, all RVs				
P [d]	9.6112534	±	0.0000061	
$T_{periastron}$	2438772.3306	±	0.0086	
K [km s^{-1}]	28.146	±	0.017	
e	0.45510	±	0.00054	
ω [deg]	329.09	±	0.14	
γ [km s^{-1}]	8.596	±	0.015	
rms [kms]	0.25			
$T_{prim.eclipse}$	2438774.139	±	0.010	
$T_{sec.eclipse}$	2438771.741	±	0.010	
$\phi_{prim.eclipse}$	0.1882	±	0.0010	
$\phi_{sec.eclipse}$	0.9387	±	0.0010	

Whereas the periods derived for the old data set (solution II) and the new one (solution III) are in good agreement, it is striking that both data sets can be linked in phase only by a period which significantly differs from the periods of the individual data sets (the deviations are given in Table 2 in parenthesis). The presence of apsidal motion can be excluded because of two reasons: first, our computer program handles apsidal motion as well and the resulting contribution is not significant at all ($d\omega/dt = -0.002 \pm 0.030°/y$); second, and this is a physical reason, the phase lag of about 0.2 between the two data sets corresponds to an apsidal advance of about 72°.

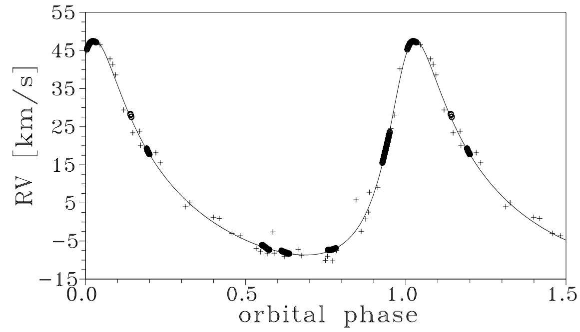

Fig. 1. Orbital solution IV for HD 169981. Dots: TLS data. Plus signs: Young's RVs from Victoria.

Table 3. Mean error of a single Hipparcos measurement resp. of a single Rozhen magnitude difference value, rms_m, and averaged deviation of the time series from the mean, rms_t. In parenthesis we give the mean scatter calculated without the values inside the assumed eclipse.

photometry	rms_m [mmag]	rms_t [mmag]
Hipparcos: HD 169981	6.6	8.2 (6.8)
Rozhen: HD 169981 – HD 168913	4.3	7.2 (6.2)
Rozhen: HD 168913 – HD 168914	4.3	4.0

During this time interval the shape of the orbital curve should have essentially changed. Comparing the orbital solutions II and IV the orbital curves are almost identically, however.

As our photometric observations show (see Sect. 4), HD 169981 could probably be classified as an eclipsing binary. Accordingly, at the bottom of Table 2 we give the parameters of the eclipse. Unfortunately, no spectrograms were taken sufficiently near to the phase of primary eclipse.

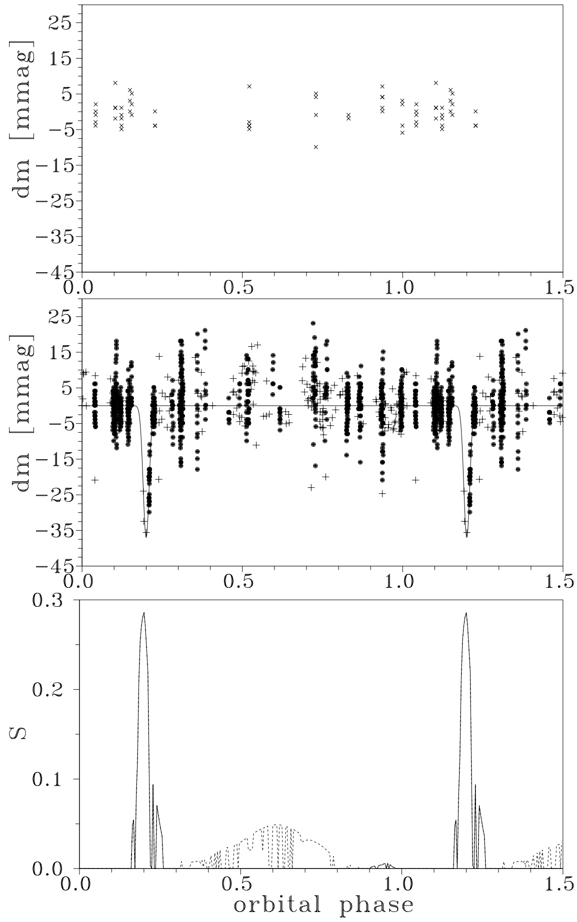

Fig. 2. Photometry versus orbital phase (phase 0 corresponds to periastron passage). **Top:** comparison minus check star of the Rozhen photometry. The mean difference in magnitude was already subtracted. **Center:** light curve of HD 169981 folded with the $9\overset{d}{.}61$ orbital period. Plus signs: Hipparcos data; circles: Rozhen data, in the sense HD 169981 – HD 168913. **Bottom:** reduction in the sum of squares by a free Gaussian fit centered at various phase positions. Solid line: Gaussian fit with negative amplitude (dips); dashed line: Gaussian fit with positive amplitude; see text.

4. Photometric behaviour

In the upper panel of Fig. 2 we show the measurements comparison (HD 168913) minus check star (HD 168914), normalized to zero, of the Rozhen photometry. In the panel under it we give the Rozhen and Hipparcos photometry of HD 169981. Table 3 lists the rms obtained from the individual errors of measurement as well as the rms of the time series. The rms for the Rozhen photometry were estimated from the scatter of the comparison – check star values within single nights. The given accuracy was also established for the U and B filters. For the Hipparcos data we used the individual errors given in the catalogue.

According to the ground-based data published in the literature, the brightness of HD 169981 should show only a weak variability of at most 10 mmag (Rufener & Bartoldi 1982). But among the Rozhen observations is a set near June 5, 2000 ($N_r = 25$), which shows a dip of about 30 mmag near $\phi = 0.20$. A few Hipparcos observations were made near to the Rozhen minimum and they confirm the dip, although both photometric data sets show considerable scatter. Comparing the predicted phase of the primary eclipse given in Table 2 with the observed light minimum, we find a good agreement.

No photometric variability is known of the comparison star HD 168913 though the star is a 5.5-d spectroscopic binary. The constancy of brightness within the derived limit of accuracy of about 4 zo 5 mmag is well confirmed by the values of rms_m and rms_t of Table 3. Also the mean scatter of the time series of the Hipparcos data of HD 169981 is comparable to the mean error of measurement if we exclude the data taken during the presumed eclipse. Only the scatter of the time series taken at Rozhen is larger by a factor of 1.4 than the mean photometric error.

The latter fact rises some doubts if the presumed eclipse is one single event or if there are further significant instances of dips or peaks in the light curve. So one could argue that other combinations of fluctuations and neighboured gaps can be interpreted as dips caused by an occultation as well. In that case the coincidence of the strongest dip with the time of primary eclipse predicted by the orbital solution would be a pure accident.

To check this we have computed Gaussian fits to the observed light curve, with free amplitude and half width, at various positions in orbital phase. In the bottom panel of Fig. 2 we show the reduction in the sum of squares following from these fits in the form of a phase diagram. The ordinate is $S = 1 - \sigma^2/\sigma_0^2$ where σ^2 is the variance of the residuals of the fit and σ_0^2 is the total variance of the data. A remarkable reduction in the sum of squares (of nearly 30%) is only achieved at the phase position of the primary eclipse. All other contributions practically vanish (for completeness we have also allowed for Gaussian-like peaks in the light curve (dashed line) which reach about 5% in maximum).

The coincidence of the dominating peak in the phase diagram with the position of the primary eclipse following from the spectroscopic orbit is striking and so we think that there is a strong likelihood that the observed decrease in brightness was caused by the occultation of one component. Unfortunately, the eclipse is not well covered by our photometry. The solid curve in the middle panel of Fig. 2 shows the best Gaussian fit (maximum reduction of the sum of squares) to the presumed eclipse minimum with the most observations occurring on its ascending branch.

5. Physical elements of the binary

In the following, pursuing our assumption that HD 169981 is an eclipsing binary, we will assume that the orbital inclination of the system is $\pi/2$. For simplicity we will neglect influences of a variable cross-section or any reflection effects of the two photospheres.

5.1. Stellar masses and absolute orbit

The mass of the secondary is related to that of the primary (in $M_\odot$) by the mass function

$$f(M) = \frac{M_2^3}{(M_1+M_2)^2} = 1.0359 \times 10^{-7}\, K_1^3\, P\,(1-e^2)^{3/2} \quad (1)$$

where the orbital period P is expressed in days and the RV semi-amplitude K_1 in $\mathrm{km\,s^{-1}}$. Inserting the corresponding values of orbital solution IV in (1) we obtain $f(M) = 0.0157\ M_\odot$. The semi-amplitude K_2 of the fainter star follows from the mass ratio, and the semi-major axis a of the orbit, expressed in $R_\odot$, from

$$a = 0.01976\,(K_1+K_2)\,P\,\sqrt{1-e^2}. \quad (2)$$

5.2. Expected central depths of the eclipses

One can also estimate the expected depths of the primary and secondary eclipses. Outside eclipse we observe the total luminosity $L_{\mathrm{total}} = L_1 + L_2$, but which is reduced during eclipse to $L = L_1 + L_2 - \Delta L$. The decrease in magnitude is given by

$$\Delta m = -2.5\,\log\left(1 - \frac{\Delta L}{L_{\mathrm{total}}}\right). \quad (3)$$

For the primary eclipse we have to integrate over the central part of the primary covered by the secondary. For a rough estimation we will assume undistorted spherical stars with a central symmetric surface light distribution:

$$\Delta L = 2\pi \int_0^\eta I_1(r)\, r\, \mathrm{d}r \quad (4)$$

where $\eta = R_2/R_1$ is the ratio of the stellar radii. In addition, we assume a limb-darkening law

$$I_1(r) = \frac{1+\beta\sqrt{1-r^2}}{1+\frac{2}{3}\beta}\,\frac{L_1}{\pi} \quad (5)$$

where β is the limb-darkening coefficient. The expression is normalized so that the integral of I_1 over the entire surface of the primary yields L_1. The integration of Eq. (4), together with Eq. (3), gives the central depth of the primary eclipse, i.e.

$$\Delta m_1 = -2.5\log\left[\frac{(1+\frac{2}{3}\beta\sqrt{x})\,x}{1+\frac{2}{3}\beta}\,\frac{L_1}{L_{\mathrm{total}}}\right] \quad (6)$$

where $x = 1-\eta^2$. The decrease depends on the ratios of the stellar radii and luminosities, and on the limb-darkening coefficient.

Since we assumed $i = \pi/2$ and $R_2 < R_1$, the secondary eclipse is total and the minimum light of the central depth is simply given by

$$\Delta m_2 = -2.5\log\left(1 + \frac{L_2}{L_1}\right). \quad (7)$$

5.3. Expected total duration of the primary eclipse

Figure 3 shows the secondary at the positions of first (S_1) and last (S_2) contact of primary eclipse. The orbital geometry reflects the orbital elements given in Table 2 and the stellar radii are scaled to the components composition A2 III + K3 V as listed in Table 3. The total duration Δt_1 of the primary eclipse can be easily estimated if we assume constant orbital velocity during the eclipse, setting r_1 and r_2 (Fig. 3) equal to $r =$ const. (otherwise we have to use the more complicated formulae given by Kopal 1959). We approximate further the orbital section L by the sum of the stellar diameters. The duration of the eclipse is then

$$\Delta t_1 = \frac{2}{v}\,(R_1+R_2) \quad (8)$$

where v is the relative velocity between the two components at the moment of minimum light. It is given by

$$v^2 = G\,(M_1+M_2)\left(\frac{2}{r} - \frac{1}{a}\right) \quad (9)$$

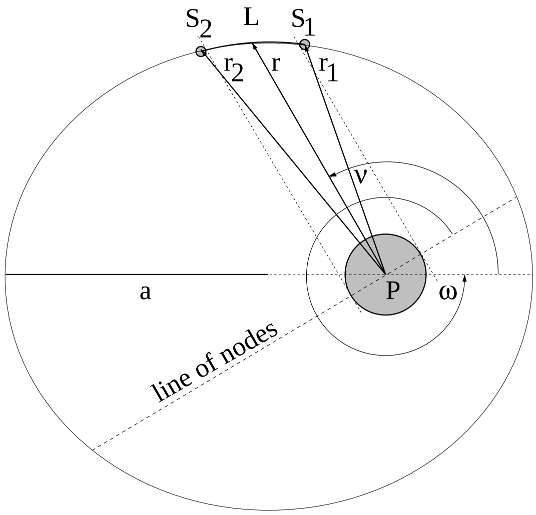

Fig. 3. Orbital geometry of HD 169981 showing the primary (P) and the positions of the secondary at the moments of first (S_1) and last (S_2) contact during primary eclipse. The radius vector r points towards the observer. L is the orbital section passed by the secondary during the eclipse.

Table 4. Calculated stellar parameters, absolute semi-major axis, and expected properties of the eclipses (see Sect. 5.4).

model		I	II
primary		A2 V	A2 III
M_1	$[M_\odot]$	2.8	4.0
R_1	$[R_\odot]$	2.2	5.0
secondary		K7 V	K3 V
M_2	$[M_\odot]$	0.56	0.70
R_2	$[R_\odot]$	0.65	0.75
K_2	$[\mathrm{km\,s^{-1}}]$	141	161
a	$[R_\odot]$	28	32
$a_{\min}$	$[R_1]$	6.9	3.5
Δm	[mag]	6.8	6.3
Δm_1	[mmag]	123	30
Δm_2	[mmag]	2.1	3.3
Δt_1	[hr]	7.6	13.6

and the radius vector r by

$$r = \frac{a\,(1-e^2)}{1+e\,\cos\nu} \tag{10}$$

where ν is the true anomaly. At the moment of superior conjunction it is $\omega + \nu = \pi/2$ and, substituting the semi-major axis a using the third Keplerian law, we finally get

$$\Delta t_1 = 1.82\,\frac{(R_1+R_2)\,P^{1/3}}{(M_1+M_2)^{1/3}}\sqrt{\frac{1-e^2}{1+e^2+2\,e\sin\omega}} \tag{11}$$

where Δt_1 is expressed in hours (masses and radii are again in solar units and the period P in d).

5.4. Results

With the value of the mass function $f(M) = 0.0157\ M_\odot$, given in 5.1, and the spectral type A2 of the primary the binary configuration of HD 169981 can be estimated. However, some uncertainty exists about the luminosity class of the primary. In the older literature spectral types A2 V (Osawa 1959; Eggen 1960) and A2 IV (Cowley et al. 1969) can be found, whereas Abt & Morell (1995) or Grenier et al. (1999) give A2 III. Therefore, in Table 4 we have calculated the eclipse parameters for two models which fulfill the mass function: one with A2 V + K7 V, the other with A2 III + K3 V. The masses, radii and semi-major axis a are expressed in corresponding solar units, and the minimum distance of both components $a_{\min} = (1-e)\,a$ in radii of the primary. Δm is the expected difference in magnitude between primary and secondary. For the radii and the luminosities of the component stars we adopted the values tabulated by Schmidt-Kaler (1981). The depths of the primary and secondary eclipses, Δm_1 and Δm_2, were calculated assuming a limb-darkening coefficient of 1.5. The last column gives the expected time of total duration of the primary eclipse in hours. Comparing the given values with the observed dip in the lightcurve it is clear that only model 2 fits the photometric data and that the primary should be very probably a giant star.

6. Discussion

HD 169981 has been known for more than three-quarters of a century to be a spectroscopic binary. Based on this time period of about 80 years, the combination of the old RVs given by Young and our RVs allows us to derive precise orbital elements. However, a phase shift of about 2 d between both data sets exists so that the orbital period has possibly to be corrected. The origin of this phase shift cannot be clearified on the basis of the present observational material, although apsidal motion can be ruled out. One possible explanation could be a temporary variation of the orbital period between the two epochs of observation caused by the interaction with a third component at a great distance. Such sinusoidal variations had been observed e.g. for U Oph or AK Her (Panchatsaram & Abhyankar 1982).

Our recent photometric observations characterize the star probably as an eclipsing binary as well. From Table 4 we can see that, independent of the exact luminosity class of the primary, the hypothetical secondary is a low-mass star which cannot give rise to a measurable contribution to the spectrum at the wavelengths observed, and the depth of the secondary eclipse should not exceed about 3 mmag. Both the depth of the primary eclipse and its total duration strongly depend on the luminosity of the primary. The calculated depth of about 30 mmag for a giant of spectral type A2 is in good agreement with the depth of the dip observed in the HD 169981 light curve and with the luminosity class given by Abt & Morrell (1995). The predicted duration of about 14 hours, which spreads over 0.06 in orbital phase, is also compatible with our measurements. Without doubts more observations are necessary, but the time to cover the expected eclipse is extremely limited.

Outside the eclipse a few Hipparcos and Rozhen data deviate significantly from the mean behaviour, however.

As we have shown these deviations are not correlated with the orbital phase. A search for periods in the residuals of the orbital solution gives no periodicity; only the 1 d alias peaks are present.

Acknowledgements. K.P. would like to thank the Astrophysikalisches Institut Potsdam for its warm hospitality during his recent visit. He also acknowledges for support from the Deutsche Forschungsgemeinschaft, 436 BUL 113-102-0 and the grant F-826 by the Bulgarian National Science Foundation. We thank the referee, Dr. C. Sterken, for his comments which helped to improve the paper, and Dr. E. Griffin for a careful proofreading of the manuscript.

References

Abt, H. A., & Morrell, N. I. 1995, ApJS, 99, 135

Cowley, A., Cowley, C., Jaschek, M., & Jaschek, C. 1969, AJ, 74, 375

Eggen, O. J. 1960, MNRAS, 120, 563

Grenier, S., Baylac, M. O., Rolland, L., et al. 1999, A&AS, 137, 451

Kopal, Z. 1959, Close Binary Systems (Chapman & Hall, London), 385

Osawa, K. 1959, ApJ, 130, 159

Panchatsaram, T., & Abhyankar, K. D. 1982, in Binary and Multiple Stars as Tracers of Stellar Evolution, ed. Z. Kopal, & J. Rahe (D. Reidel Publ. Co.), 47

Rufener, F., & Bartholdi, P. 1982, A&AS, 48, 503

Schlesinger, F. 1908, Publ. Allegheny Obs., 1, 35

Schmidt-Kaler, Th. 1981, Physical parameters of the stars, in Landolt-Börnstein, Zahlenwerte und Funktionen aus Naturwissenschaften und Technik, Neue Serie, Gruppe VI: Astronomie, Astrophysik und Weltraumforschung; Band 2 b (Springer-Verlag Berlin/Heidelberg/New York), 28

Young, R. K. 1919, Pub. Dom. Astrophys. Obs., 1, 131