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THE TWO VARIABLES IN THE TRIPLE SYSTEM HR 6469=V819 HER: ONE ECLIPSING, ONE SPOTTED

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ABSTRACT

A complete *BV* light curve, from 14 nights of good data obtained with the VU-TSU automatic telescope, are presented and solved with the Wilson-Devinney program. Third light is evaluated, with the companion star brighter by $0^{\rm m}.58$ in *V* and $0^{\rm m}.11$ in *B*. The eclipses are partial. Inferred color indices yield F2 V and F8 V for the eclipsing pair and G8 IV-III for the distant companion star. After removing the variability due to eclipses, we study the residual variability of the G8 IV-III star over the ten years 1982 to 1992. Each yearly light curve is fit with a two-spot model. Three relatively long-lived spots are identified, with rotation periods of $85^{\rm d}.9$, $85^{\rm d}.9$, and $86^{\rm d}.1$. The weak and intermittent variability is understood because the G8 IV-III star has a Rossby number *at the threshold* for the onset of heavy spottedness.

1. INTRODUCTION

HR 6469 was discovered as a variable star, later named V819 Her, by Boyd *et al.* (1985). It is a triple system, composed of a G5 IV star in a 5.5 yr orbit around a pair of stars in a 2.23 day orbit, the brighter of those two being an F2 V star. Boyd *et al.* (1985) found two sources of variability. First, the close pair undergoes eclipses, with primary and secondary eclipse depths in the *V* bandpass of approximately $0^{\rm m}.085$ and $0^{\rm m}.05$, respectively. Second, there was a slower, more or less sinusoidal variability with a full amplitude of $0^{\rm m}.04$ in the *V* bandpass and a period of $83^{\rm d}.2\pm0^{\rm d}.7$, presumed to result from rotational modulation of the spotted surface of the G5 IV star. Strassmeier *et al.* (1989) analyzed four seasons of photometry, 1984 through 1987, obtained with the same 10 in. automatic telescope which was one of those used by Boyd *et al.* (1985), and found a mean period of $81^{\rm d}.9\pm0^{\rm d}.4$ and seasonal amplitudes ranging from $0^{\rm m}.027$ to $0^{\rm m}.037$ in *V*.

This paper is one of three in this same issue, all dealing with different aspects of HR 6469. Scarfe *et al.* (1992,1994) present the latest, most complete discussion to date of the spectroscopic aspects, for both the 5.5 year orbit and the 2.23 day orbit. Wasson *et al.* (1994) presented 90 eclipse timings, of both primary and secondary. One was published elsewhere but the other 89 were determined from photoelectric observations made at many different observatories in various bandpasses. From those 90 timings they derived an improved linear ephemeris for the eclipsing pair, after taking into account the time-delay effect expected from the eclipsing pair's motion in the 5.5 year orbit, finding

$$T(\text{pri.min.})=\text{JD(hel.)}2{,}448{,}546.5991+2^{\rm d}.2296296\ \ E+\Delta T, \qquad (1)$$
$$\pm 13 \qquad\qquad \pm 11$$

where ΔT is the time-delay correction.

In this paper we present analysis of all available photometry, new photometry as well as that treated by Boyd *et al.* (1985) and by Strassmeier *et al.* (1989). Specifically we present a complete eclipse light curve obtained in 1992 in the *V* and *B* bandpasses with the 16 in. automatic telescope operated by Vanderbilt University and Tennessee State University (VU-TSU), use the Wilson–Devinney program to solve it, and describe the evolution of G5 IV star's variability over the last ten years.

2. THE COMPLETE LIGHT CURVE IN *V* AND *B*

V819 Her was monitored with the VU-TSU 16 in. automatic photoelectric telescope on 23 nights in June of 1992 around its time of opposition in order to define, with high precision, all phases of the eclipsing pair's light curve at a single epoch. The observations were made with the new temperature controlled, high precision photoelectric photometer described by Henry & Hall (1993) that uses a CCD camera for finding stars and quickly centering them in the focal plane diaphragm. The telescope was programmed to measure V819 Her and its comparison and check stars through *V* and *B* filters in the sequence K,S,C,V,C,V,C,V,C,S,K, where K is the check star (69 Her), C is the comparison star (HR 6444), and S is the sky position. A diaphragm 55 arcsec in diameter was used, which included all three components of V819 Her. During the 23 nights this sequence was repeated continually as long as the star remained within the telescope's accessible hour angle window (4.5 h east to 4.0 h west at the declination of V819 Her) or the weather sensors detected a condition necessitating closure of the observatory roof. Each completed sequence, termed a group observation, was reduced differentially with mean extinction and transformation coefficients, resulting in three *V* and *B* differential magnitudes of V819 Her (in the sense variable minus comparison) and two differential magnitudes of 69 Her (in the sense check minus comparison). Each group mean in *V* and *B* was then considered a single observation of V819 Her.

The internal precision of each V819 Her observation can be estimated from the standard error of the group mean (SEM), calculated from the standard deviation of the three differential measures used to form each mean. Since the telescope observes anytime it can find stars, these SEMs are needed to weed out observations taken under relatively poor photometric conditions. Nine of the 23 nights had average SEMs greater than $0^{\rm m}.01$ and so were considered nonphotometric. The remaining 14 nights, those yielding superior data, are listed in Table 1. For each of those nights the number of good group observations in *V* and *B* are listed along with the nightly average SEM, in magnitudes, for each bandpass. Individual group means with a SEM greater than $0^{\rm m}.01$ have been culled from these data as well. Totals of 831 *V* and 829 *B* group means survived this "cloud filtering" process and so were retained for analysis. The SEMs for these good data averaged $0^{\rm m}.0025$ in *V* and $0^{\rm m}.0027$ in *B*.

As a check on the constancy of the comparison star and as an estimate of the external errors in the data, means of all

TABLE 1. Observations for complete light curve.

Julian date (2440000+)	obsv. in V	SEM (mag.)	obsv. in B	SEM (mag.)
8776	63	0.0024	62	0.0026
8777	38	0.0030	39	0.0038
8778	68	0.0024	68	0.0026
8779	68	0.0021	68	0.0027
8780	66	0.0036	64	0.0035
8781	38	0.0025	38	0.0028
8783	33	0.0023	33	0.0024
8784	49	0.0025	49	0.0025
8785	69	0.0027	69	0.0027
8786	69	0.0019	69	0.0025
8800	69	0.0029	69	0.0026
8801	68	0.0023	68	0.0027
8802	67	0.0021	67	0.0022
8803	66	0.0024	66	0.0027

check star differential magnitudes in V and B obtained on the 14 good nights were formed and the standard deviations of the individual check star group means from those long-term means were computed. The mean check star differential magnitudes were $-1^{\mathrm{m}}3251$ in V and $-2^{\mathrm{m}}3145$ in B. The standard deviations of the individual group means from those long-term means were $0^{\mathrm{m}}0041$ in V and $0^{\mathrm{m}}0046$ in B. The check star and the comparison star, therefore, must have been constant to better than $0^{\mathrm{m}}005$ during our time interval and, moreover, the external errors in the measurements of the variable can be no larger than this. As a more explicit check on the external errors of the observations, all of the good out-of-eclipse observations of V819 Her were fit with a $\cos 2\theta$ curve to approximate the observed ellipticity effect. The rms of the residuals of the observations from this fit were $0^{\mathrm{m}}0031$ in V and $0^{\mathrm{m}}0035$ in B.

3. SOLUTION OF THE LIGHT CURVE

Although the ten years of photometry at our disposal implicitly makes up an entire light curve of the eclipsing binary in the 2.23 day orbit, all phases within both eclipses and between the eclipses, we decided to base our light curve solution on just the photometry obtained in the summer of 1992 with the VU-TSU 16 in. automatic telescope, described above in Sec. 2. The motivation for this was twofold. First, this particular data set was especially homogeneous and also had the highest photometric accuracy. Second, it turns out that, fortuitously, during that summer of 1992 the variability of the G5 IV star, which is necessarily included in each photometric measurement, was so small as to be unimportant. We will see later, in Sec. 5, that the total range in V was only $0^{\mathrm{m}}001$.

Excluding observations made during nights of inferior photometric quality, we are left with V and B light curves consisting of 831 and 829 observations, respectively. Phase coverage is, however, good and complete. The Wilson–Devinney (WD) program (Wilson 1979) was used to solve both light curves simultaneously. Phases were computed with the ephemeris in Eq. (1) minus the ΔT term. The phase-zero point was adjusted as part of our least-squares light curve solution and an O−C residual with respect to the above ephemeris was found, namely, $+0^{\mathrm{d}}0034\pm0^{\mathrm{d}}0003$. The deduced time of mid-primary eclipse for the entire mean light curve in V and B therefore is JD (hel.) 2 448 780.7136 $\pm0^{\mathrm{d}}0003$. This value was one of the 90 eclipse timings analyzed by Wasson *et al.* (1994). We formed 143 normal points in V and B light and assigned weights equal to the number of observations per normal, typically 15 around the maxima but only 1 to 3 in the minima. Standard deviations of 0.0031 and 0.0034 light units in V and B, respectively, needed by the differential corrections program for curve-dependent weighting (Wilson 1979), were obtained by making averages of standard deviations from least-squares straight line fits at four different phase ranges in the maxima. Comparing those numbers with similar standard deviations in the minima, we found that scatter is essentially proportional to light level. That told us to use a value of 2 for the input integer NOISE, which specifies the scaling of the light-dependent weights in the WD differential corrections program.

Our solution is listed in Table 2, where fixed parameters are distinguished from adjusted parameters by their lack of probable errors. Subscripts 1, 2, 3 refer to the F2 V star, its unseen companion in the eclipsing pair, and the distant G5 IV star, respectively. The mean surface effective temperature of 7000 K for the primary component was adopted according to its F2 V spectral type. The linear cosine-law limb-darkening coefficients are for stars with effective temperatures $T=7000$ K, 6125 K, and $\log g=4.0$, 4.25. They were obtained by interpolation in the tables of Van Hamme (1994). Gravity-darkening coefficients 1.0, 0.32, and albedos 1.0, 0.5 were used for components 1 and 2, respectively. Judged by its spectral type, component 1 is somewhat close to the transition of main-sequence stars with radiative and convective envelopes. A second solution (with $g_1=0.32$ and $A_1=0.5$) was made, without any improvement in the overall sum of the squares of the residuals, so we present only the first solution. Both eclipses are partial, with 27% of the F2 V star's projected area eclipsed at primary minimum and 57% of the other star's projected area eclipsed at secondary minimum.

The fitted light curves are shown in Figs. 1 and 2. The rms residual (observed minus fit) is 0.0039 for the V light curve and 0.0036 for B, in units of the total light at phase 0.25. In magnitude units these correspond to $0^{\mathrm{m}}0042$ and $0^{\mathrm{m}}0039$, which compare favorably with the previously determined external errors ($0^{\mathrm{m}}0031$ and $0^{\mathrm{m}}0035$ in V and B).

The third light was, of course, included as an adjustable parameter. It is interesting to note that a trial solution without third light resulted in a substantially worse fit, with rms errors larger by a factor 2.5! We find that third light amounts to 0.630 ± 0.017 in V and 0.525 ± 0.022 in B, both in units of total light at phase 0.25. Comparing these numbers with the fraction of total light due to components 1 and 2 combined, leads to magnitude differences (close pair minus third star) of $+0^{\mathrm{m}}58$ in V and $+0^{\mathrm{m}}11$ in B.

Since V819 Her is a detached system, its mass ratio cannot be determined from the light curve. This parameter was kept fixed at the value $q=0.72$, which has been determined from the spectroscopy of Scarfe *et al.* (1994).

For the combined light of all three stars, we adopt

TABLE 2. Light curve solutions for HR 6469=V819 Her.

element	syncronous	asynchronous
e	0.0	0.0
ω	undefined	undefined
F_1	1.0	0.5
F_2	1.0	1.0
ϕ	$0^{p}.00152 \pm 0^{p}.00014$	$0^{p}.00152 \pm 0^{p}.00014$
q	0.72	0.72
g_1	1.0	1.0
g_2	0.32	0.32
A_1	1.0	1.0
A_2	0.5	0.5
x_1 in V	0.497	0.497
x_1 in B	0.605	0.605
x_2 in V	0.561	0.561
x_2 in B	0.691	0.691
i	$81^{\circ}.00 \pm 0^{\circ}.36$	$80^{\circ}.63 \pm 0^{\circ}.33$
T_1	7000 K	7000 K
T_2	6099 ± 14 K	6083 ± 15 K
Ω_1	6.080 ± 0.044	5.982 ± 0.042
Ω_2	6.726 ± 0.087	6.802 ± 0.112
$L_1/(L_1+L_2)$ in V	0.781 ± 0.035	0.792 ± 0.029
$L_1/(L_1+L_2)$ in B	0.802 ± 0.036	0.813 ± 0.030
l_3 in V (*)	0.630 ± 0.017	0.604 ± 0.015
l_3 in B (*)	0.525 ± 0.022	0.490 ± 0.020
r_1 (pole)	0.1862 ± 0.0015	0.1896 ± 0.0015
r_1 (point)	0.1888 ± 0.0016	0.1915 ± 0.0016
r_1 (side)	0.1872 ± 0.0016	0.1899 ± 0.0015
r_1 (back)	0.1884 ± 0.0016	0.1911 ± 0.0016
r_1 (equal volume)	0.1873	0.1902
r_2 (pole)	0.1287 ± 0.0020	0.1270 ± 0.0025
r_2 (point)	0.1297 ± 0.0021	0.1279 ± 0.0026
r_2 (side)	0.1290 ± 0.0020	0.1273 ± 0.0025
r_2 (back)	0.1296 ± 0.0021	0.1278 ± 0.0026
r_2 (equal volume)	0.1291	0.1274

*) in units of the system's total light at phase 0.25

$V=5^{m}.57$ and $B-V=+0^{m}.695$ as means of values given in six different sources which are enumerated by Scarfe *et al.* (1994). Using the fraction of total light at phase 0.25 due to each individual star according to the light curve solution in Table 2, we find the apparent V and B magnitudes and $B-V$ color indices listed in Table 3. The absolute V magnitudes listed as well were derived by using the value $0''.0145 \pm 0''.0002$ given for the parallax by Scarfe *et al.* (1994) and by assuming negligible interstellar absorption and/or reddening. The numbers in Table 3 are in excellent agreement with the observed F2 V spectral class of star 1. The numbers for star 2 correspond to a spectral class of about F8 V, which also is in agreement with the effective temperature of 6099 K obtained directly from the light curve solution. The numbers for star 3, neither the $B-V$ nor the M_V, are not so consistent with the spectral class G5 IV determined originally by Strassmeier & Fekel (1990). G9 IV-III would be better or, if we allowed for $0^{m}.02$ of color excess, G8 IV-III. Scarfe *et al.* (1992) had said the luminosity class was closer to III than IV, and Scarfe *et al.* (1994) most recently have decided the star's spectrum is somewhere on a diagonal between G5 IV and G8 III and is matched closely by G7 IV-III.

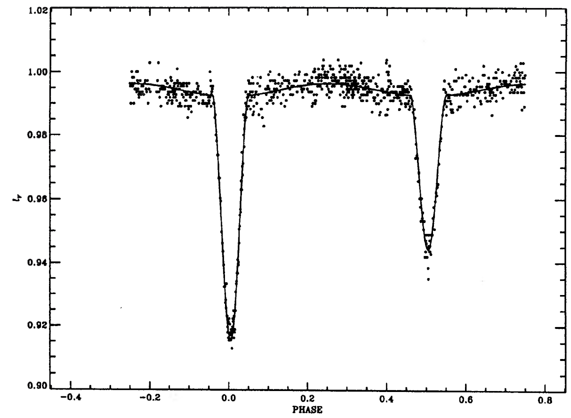

FIG. 1. V band light curve of V819 Her. Each point is one of the 831 individual observations made by the VU-TSU automatic telescope on the 14 nights listed in Table 1. The solid curve represents the elements listed in Table 2 for the synchronous solution. Light from the more distant third star, brighter by $0^{m}.6$, is included as an additive constant, because the third star was insignificantly spotted at that epoch. The curvature between eclipses results solely from the combined ellipticity and reflection effects.

We know the masses of both stars in the eclipsing pair from the spectroscopic work of Scarfe *et al.* (1994), especially so now that our light curve solution has determined the orbital inclination exactly. The orbital period is also known (Wasson *et al.* 1994). This gives us the orbital semimajor axis in linear units, namely, $9.96 \pm 0.10 R_{\odot}$. From the volume-equivalent radius of each star, as given in Table 2, we then get the absolute radii which are given as the last entries in Table 3. The F2 V star appears to have evolved somewhat from the zero-age main sequence; the F8 V star appears not to have evolved appreciably.

Scarfe *et al.* (1994) were surprised to find that the $v \sin i$ value they measured for the F2 V star implied rotation at

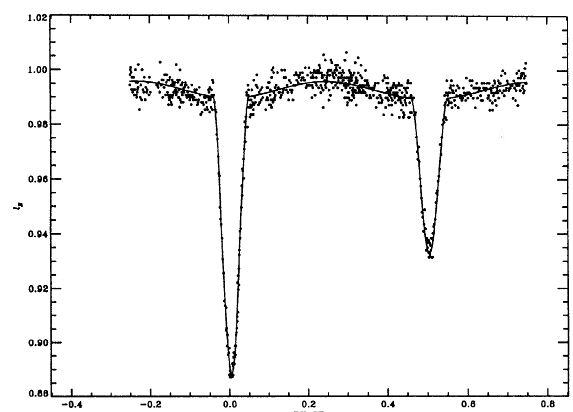

FIG. 2. B band light curve of V819 Her. Each point is one of the 829 individual observations made by the VU-TSU automatic telescope on the 14 nights listed in Table 1. The solid curve represents the elements listed in Table 2 for the synchronous solution. Light from the more distant third star, brighter by $0^{m}.1$, is included.

TABLE 3. The three components of V819 Her.

Component	1	2	3
Spectral Class	F2 V	F8 V	G8 IV-III
V (mag.)	6.92 ±.07	8.30 ±.17	6.07 ±.03
B (mag.)	7.31 ±.07	8.83 ±.19	6.97 ±.04
B-V (mag.)	0.39 ±.09	0.54 ±.24	0.90 ±.05
M_V (mag.)	2.73 ±.08	4.11 ±.17	1.88 ±.04
Radius ($R_\odot$)	1.87 ±.02	1.29 ±.02	[7]

only half the synchronous rate. For this reason we made a third solution, with $F_1=0.5$ instead of 1.0, and list its elements in Table 2 for comparison. Corresponding entries are very similar, and not different by more than would be expected from the formal uncertainties in both. The rms residuals in the V and B light curves were virtually identical, 0.0038 and 0.0035 in light units or $0\overset{m}{.}0041$ and $0\overset{m}{.}0038$. We did try solving for F_1, rather than fixing its value, but the huge formal uncertainty which resulted indicated that this parameter is effectively indeterminate.

4. THE TEN-YEAR DATA BASE

The photometry discussed originally by Boyd *et al.* (1985) was stored as file no. 150 of the I.A.U. Archive for Unpublished Photometry of Variable Stars (Breger 1988) and thus was accessible. The four years of extensive *UBV* photometry obtained with the 10 in. automatic telescope has been published (Boyd *et al.* 1990) and thus was accessible as well. The analysis by Strassmeier *et al.* (1989) was based on a subset of those four years, in *V* only. The VU-TSU 16 in. automatic telescope has been observing HR 6469 in the one-point-per-night mode since 1987 November, in *UBVRI* or in *BV*, so we have these four years of data in addition to the one-star-all-night-long *BV* photometry discussed in Sec. 2. Observers contributing additional photometry used in this paper are listed in Table 4.

TABLE 4. Photometric observers.

Observatory Name	Location	Aperture	Observers
Barksdale	Florida	36 cm	Barksdale
Braeside	Arizona	41	Fried
Dublin	Delaware	10	Nielsen
E.T.S.U.	Tennessee	29	Powell
Green Grove	Utah	20	Green
Lines	Arizona	51	Lines, Lines
Ragland	Virginia	18	Tatum
Riverdale	New York	25	Chang
Rolling Ridge	Pennsylvania	20	Reisenweber
St. Oakes	Virginia	15	Shervais
S.W.O.S.U.	Oklahoma	36	Rogers
Sunset Hills	California	20,36	Wasson

TABLE 5. Data groups.

Median epoch	Number of observations	Δt (days)
1982.65	45	114
1983.58	119	177
1984.45	391	282
1985.40	164	294
1986.28	61	148
1987.48	90	252
1988.59	150	200
1989.48	105	261
1990.45	103	279
1991.27	93	163
1992.35	1180	107

All of the photometry, previously published and new in this paper, was done differentially with HR 6444 as the comparison star, was corrected for differential atmospheric extinction, and was transformed differentially to the appropriate bandpass of the *UBVRI* system. Since the database was by far the most complete in the *V* bandpass, we have limited our analysis (of the G8 IV-III star's variability) which follows to that one bandpass.

The *V* band photometry obtained with the 10 in. automatic telescope between JD 2,446,218.9 and 2 446 241.8 was corrected for what Boyd *et al.* (1990) called Problem D, by using the value $\Delta(B-V)=-0\overset{m}{.}35$ in the equation

$$\Delta V(\text{corr.})=\Delta V(\text{uncorr.})-0\overset{m}{.}55\Delta(\text{B}-\text{V}) \quad (2)$$

which they recommend. Problem C discussed by Boyd *et al.* (1990) was judged not to be a problem because both HR 6469 and its comparison star are sufficiently faint, according

TABLE 6. Spot parameters.

data set (year)	P(α) (days)	t(α) (JD)	a(α) (mag.)	P(β) (days)	t(β) (JD)	a(β) (mag.)	m(max) (mag.)	r.m.s. (mag.)
1982.65	79.6 ±2.0	5162.3 ±1.3	0.045 ±.001	88.6 +4.8	5216.3 ±1.9	0.040 ±.002	-0.004 ±.001	0.015
1983.58	79.9 ±1.4	5559.1 ±1.4	0.030 ±.002	85.2 +1.4	5591.4 ±1.1	0.024 ±.001	-0.009 ±.001	0.014
1984.45	82.6 ±1.6	5821.4 ±1.0	0.020 ±.001	[85]	5854.7 ±2.0	0.010 ±.002	+0.002 ±.001	0.020
1985.40	87.6 ±1.7	6191.0 ±1.9	0.018 ±.002	80.1 +1.2	6245.8 ±0.7	0.029 ±.001	-0.011 ±.001	0.015
1986.28	88.0 ±1.3	6487.1 ±1.1	0.032 ±.003	[85]	6530.8 ±3.7	0.006 ±.004	-0.007 ±.002	0.012
1987.48	81.9 ±1.1	6927.1 ±1.2	0.018 ±.001	[85]	6972.7 ±6.8	0.003 ±.001	+0.001 ±.001	0.006
1988.59	85.6 ±2.8	7348.0 ±2.5	0.010 ±.003	78.8 +2.9	7391.0 ±2.3	0.007 ±.002	-0.002 ±.001	0.011
1989.48	86.0 ±3.6	7659.2 ±2.9	0.012 ±.003	[85]	7708.9 ±14.3	0.004 ±.004	-0.007 ±.002	0.016
1990.45	[85]	7994.2 ±5.9	0.009 ±.005	[85]	8021.7 ±5.6	0.008 ±.003	-0.008 ±.002	0.014
1991.27	[85]	8304.9 ±5.6	0.005 ±.002	[85]	8340.9 ±3.9	0.006 ±.002	-0.018 ±.001	0.011
1992.35	[85]	8782.9 ±1.4	0.005 ±.001	[85]	8814.0 ±0.8	0.006 ±.001	-0.005 ±.001	0.006

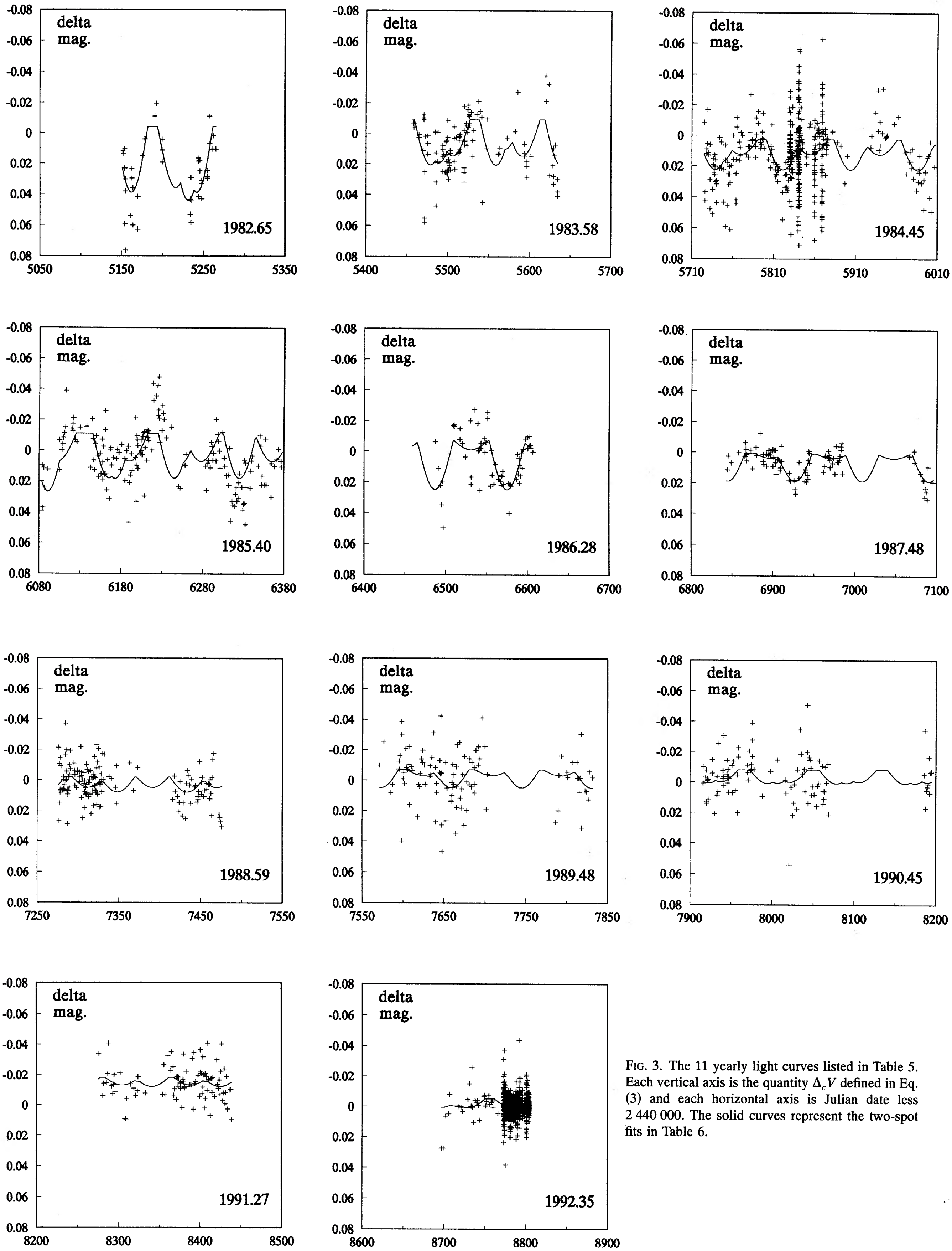

FIG. 3. The 11 yearly light curves listed in Table 5. Each vertical axis is the quantity $\Delta_c V$ defined in Eq. (3) and each horizontal axis is Julian date less 2 440 000. The solid curves represent the two-spot fits in Table 6.

to Hall *et al.* (1986). A few ΔV magnitudes within the time interval affected by Problem E were apparently grossly in error and were excluded.

5. VARIABILITY OF THE G8 IV-III STAR

To investigate the variability (in the composite light) produced by the G8 IV-III star, we first removed the variability produced by the eclipsing pair. We did this by using the 1992 Summer database of 16 in. photometry, described in Sec. 2, to prepare a light curve with phase computed using the ephemeris in Eq. (1). This was put in tabular form: mean differential magnitudes, which we call $\Delta_{EB}V$, at 100 values of phase, each bin 0.01 phase units in width. It has already been explained, in the first paragraph of Sec. 2, that the G8 IV-III star's own variability during the Summer of 1992 was exceedingly slight could not have distorted the eclipsing binary's light curve in a significant way. So, differential V magnitudes cleaned of the eclipsing binary's variability are given by

$$\Delta_c V = \Delta V - \Delta_{EB} V, \tag{3}$$

where the appropriate value of $\Delta_{EB}V$ comes from the above-mentioned look-up table after the appropriate phase has been calculated from the Julian date of each ΔV, again using Eq. (1).

The $\Delta_c V$ values were analyzed as 11 separate light curves, one for each year between 1982 and 1992. Table 5 describes these data groups further, giving the median date, time interval included, and number of data in each. For exploratory purposes, we performed Fourier transforms on each and, in 10 of the 11 data groups, saw significant power in the vicinity of the 83 day periodicity found first by Boyd *et al.* (1985). Specifically, the mean was 82 days, with a standard deviation of 10 days.

Experience with many other spotted variables has shown that typically there are at least two significantly large dark areas, generally quite separated in stellar longitude. It seemed advisable, therefore, to analyze these light curves with a two-spot model, so we adopted the one of Hall *et al.* (1990). In that model there are seven parameters: the rotation period of the two spots, $P(\alpha)$ and $P(\beta)$, the Julian dates when the two spots face the Earth and produce their maximum light loss, $t(\alpha)$ and $t(\beta)$, the amount of those two light losses in magnitude units, $a(\alpha)$ and $a(\beta)$, and the magnitude of the star's hemisphere when both of those spots are turned completely out of view, $m(\max)$. Fits are found by iteration of the seven parameters, and the best fit is the one which has the absolute minimum total variance. The uncertainty in each parameter is determined as the amount, slightly larger and/or smaller than the best value, which increases the minimum total variance by the fraction $1/(n-7)$, where n is the number of data and 7 is the number of degrees of freedom. The parameters of the best fits are presented in Table 6.

In a few cases, where the period of one or both of the spots was statistically indeterminate, the value of $P(\alpha)$ or $P(\beta)$ was fixed at 84 days. These are shown as bracketed quantities in Table 6. For the 13 spot periods which were determinate, the mean was $83^{d}7$, with a standard deviation of $3^{d}4$, considerably smaller than the 10-day standard deviation, mentioned above, resulting from the sine curve fits.

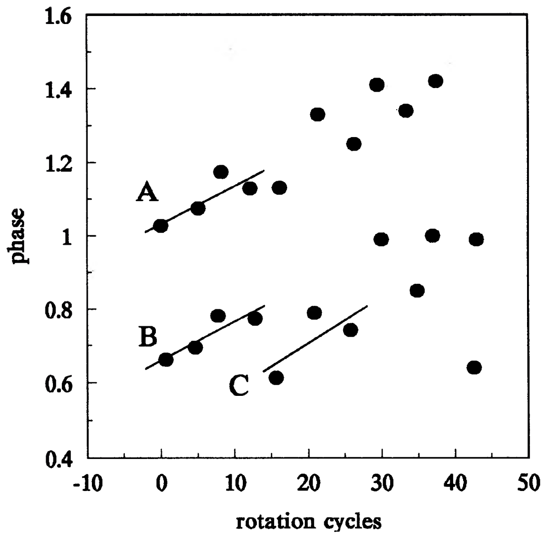

FIG. 4. The vertical axis is fractional phase of times of minimum light for the spots listed in Table 6. The horizontal axis is whole rotation cycle numbers. Both phases and cycle numbers are computed with the ephemeris in Eq. (4). The three straight-line segments identify the three relatively long-lived spots A, B, and C discussed in the text.

In Fig. 3 we plot the 11 light curves described in Table 5 along with solid curves to represent the parameters in Table 6.

Now we ask to what extent the longitudes corresponding to the values of $t(\alpha)$ and $t(\beta)$ in Table 6 show phase continuity over the 10 years of observation. To answer this question we compute phases with a provisional rotation period, namely,

$$t = \text{JD } 2{,}445{,}160.0 + 85^{d}0\ E, \tag{4}$$

and plot those phases in Fig. 4. Applying the criteria of (1) continuity in phase and (2) constancy of rotation period in Fig. 4 and (3) constancy or smoothness of evolution of spot amplitude, we judge that the same two spots existed between 1982 and 1985 and that at least one spot existed between 1986 and 1988. Line segments are drawn in Fig. 4 to represent these three spots, which we call A, B, and C. Linear fits by least squares yield the three rotation periods $85^{d}87 \pm 0^{d}44$ for A, $85^{d}87 \pm 0^{d}32$ for B, and $86^{d}1 \pm 1^{d}1$ for C. More than this we cannot say with any conviction.

Consideration of the behavior of a large number of spots (112) on a large number of different spotted stars (26) which have been observed for many years (several over a decade), led Hall & Henry (1993) to find that starspot lifetimes are related to their maximum sizes by a two-part law. As a rule, small spots have short lifetimes. We can estimate what the lifetime of the G8 IV-III star's spots should be according to those laws, bearing in mind that the rms deviation of fits to those laws was about 0.3 in the log, or a factor 2. The largest amplitude detected was in 1982, about $0^{m}04$ in V, for both spots A and B. Since both amplitudes were decreasing ever since 1982, however, it is possible that $0^{m}_{.}04$ underestimates the maximum amplitude. The G8 IV-III star accounts for 65% of the composite light in V, so the maximum intrinsic amplitude was about $0^{m}_{.}065$ in V (or larger). Using this amplitude to estimate the spot radius and adopting $7R_{\odot}$ for the G8 IV-III star, we get a lifetime of 1.5 years (or longer). This calculation makes it believable that spots A and B could have survived the 3.4 years indicated in Fig. 4. Repeating the calculation for spot C, which had a maximum amplitude of $0^{m}_{.}032$ in V, we get a maximum intrinsic amplitude of $0^{m}_{.}05$ and a lifetime of about 1.0 years. This makes it marginally believable that spot C could have survived for the 2.8 years indicated in Fig. 4. All of the other amplitudes in Table 3 are smaller than about $0^{m}_{.}01$, implying spot lifetimes of 2 months or less. For this reason we stop here in our attempt to identify points in Fig. 4 which belong to the "same" spot.

We want to say more exactly how much the G8 IV-III star varied during the 40 day time span of the VU-TSU 16 in. photometry used to solve the eclipsing binary's light curve. Since 40 days is only about half of the G8 IV-III star's rotation cycle, we used the two-spot model in a one-spot mode, with the period fixed at 85 days. The result was an amplitude of only $0^{m}_{.}001$, confirming our earlier claim that the G8 IV-III star's variability could not have interfered with the eclipsing binary's light curve solution.

Convective stars are heavily spotted (photometric variability $\geqslant 0^{m}_{.}10$) if their Rossby number (ratio of rotation period to convective turnover time) is less than 2/3 and minimally spotted (photometric variability $\leqslant 0^{m}_{.}01$) if greater than 2/3 (Hall 1991). For the G8 IV-III star we know $P(\text{rot.})=86$ days. From its spectral type of $(B-V)_0$ and its luminosity class or M_v we can estimate $\tau(\text{conv.})=115$ days (Hall 1991). Therefore, $\text{Ro}=0.75\pm0.15$, where the uncertainty here comes from uncertainties in the values used for $P(\text{rot.})$, $(B-V)_0$, and M_v. This is virtually at the Ro=2/3 threshold itself and explains nicely the detectable but annoyingly weak and intermittent photometric variability which is observed, intermediate between $\leqslant 0^{m}_{.}01$ and $\geqslant 0^{m}_{.}10$.

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