11-1991

# The 11 Year History of Starspots on V1149 Ori=HD 37824

Douglas S. Hall
*Vanderbilt University*

Francis C. Fekel
*Tennessee State University*

Gregory W. Henry
*Tennessee State University*

William S. Barksdale



## Recommended Citation

Hall, D.S.; Fekel, F.C.; Henry, G.W.; Barksdale, W.S. "The 11 Year History of Starspots on V1149 Ori=HD 37824" Astronomical Journal v.102, p.1808 (1991)

# THE 11 YEAR HISTORY OF STARSPOTS ON V1149 Ori = HD 37824

DOUGLAS S. HALL AND FRANCIS C. FEKEL
Dyer Observatory, Vanderbilt University, Nashville, Tennessee 37235

GREGORY W. HENRY
Center of Excellence in Information Systems, Tennessee State University, Nashville, Tennessee 37203

WILLIAM S. BARKSDALE
633 Balmoral Road, Winter Park, Florida 32789
*Received 25 January 1991; revised 3 July 1991*

## ABSTRACT

All available radial-velocity measures, published and unpublished, yield an improved period and a new (assumed circular) solution. The period is $53^d58 \pm 0^d02$ and conjunction (K1 giant in front) was at 2 444 325.93 $\pm$ $0^d12$. Eleven years of *V*-band photometry, published and unpublished, between 1978–1979 and 1989–1990 is analyzed. Eighteen data groups are fit with a two-spot light-curve-modeling technique. Six spots existing sometime during the 11 years are identified and the 4% range of their rotation periods is used to estimate a differential rotation coefficient of $k = 0.08 \pm 0.02$. Observed lifetimes of those six spots are consistent with times calculated on the assumption that large spots are disrupted by the shear of differential rotation. The two best observed spots each lasted about five years.

## 1. INTRODUCTION

HD 37824 = V1149 Ori is a bright ($V = 6^m6$ at maximum) SB1 with a spectral type of K1 III. It is No. 45 in the *Catalogue of Chromospherically Active Binaries* (Strassmeier *et al.* 1988).

Photometric variability was discovered by Hall *et al.* (1983), on the basis of photometry obtained during the 1980–1981, 1981–1982, and 1982–1983 observing seasons. They found the amplitude varying from year to year, the largest being $\Delta V = 0^m11$ in 1982–1983. Radial-velocity measures of F. C. Fekel, reported in that paper, indicated an orbital period of $53^d6$. Analysis of the three years of photometry indicated a period of $52^d6$, implying that the K1 giant was rotating about 2% faster than synchronously. With that period, the light-curve shape in 1982–1983 was "double humped."

Additional photometry and spectroscopy, both predating that reported by Hall *et al.* (1983), were published later. Spectroscopy by Balona (1987) yielded an orbital period of $53^d58$. Photometry by Lloyd Evans & Koen (1987) was consistent with Balona's period and showed a double-humped light curve which varied in amplitude from year to year.

Using data obtained with a 10 in. automatic telescope, Strassmeier *et al.* (1989) analyzed photometry from the 1983–1984, 1984–1985, and 1985–1986 observing seasons. They found photometric periods ranging from $51^d1$ to $54^d4$ and amplitudes which increased from $\Delta V = 0^m2$ to $0^m4$. The light curve's double-humped shape was present in their first season but absent in the last two.

With an 11 year baseline in photometric coverage, from the 1978–1979 season of Lloyd Evans and Koen to the 1989–1990 season reported in this paper, and with evidence of a light curve which changes dramatically in both amplitude and shape, V1149 Ori is ripe for a study of the evolution of its starspots, which we presume are responsible for its variability.

## 2. REFINEMENT OF THE ORBITAL PERIOD

The radial-velocity measures of Fekel mentioned by Hall *et al.* (1983) were not published in that paper but they, along with two more obtained more recently, were tabulated by Fekel *et al.* (1986, Table 4). In addition we have one measure ($29.4 \pm 0.5$ km/s at JD 2444 512.895) obtained by Bopp (1983) at Kitt Peak National Observatory.

We could combine these with the earlier radial-velocity measures published recently by Balona (1987, Table 2). Because Balona's solution had yielded an orbital eccentricity which was almost zero to within its uncertainty, we assumed $e = 0$ exactly and thus used a sine-curve fit to find the best period and to solve the combined radial-velocity curve. The resulting parameters are given in Table 1 and are represented as the solid curve in Fig. 1, where the individual radial-velocity measurements of Balona and Fekel are plotted with dif-

TABLE 1. Spectroscopic orbit.

| element | Balona (1987) | this paper |
|---|---|---|
| Period (days) | 53.58 ± 0.05 | 53.58 ± 0.02 |
| $\gamma$ (km/sec) | 27.1 ± 0.4 | 26.9 ± 0.3 |
| $K_1$ (km/sec) | 25.3 ± 0.7 | 26.2 ± 0.5 |
| e | 0.03 ± 0.02 | 0 (assumed) |
| $\omega$ (degrees) | 328.4 ± 25.6 | undefined |
| JD(peri.) | 2444334.8 ± 3.8 | undefined |
| JD(conj.)* | 2444326.3 ± 3.8 | 2444325.93 ± 0.12 |

* K1 giant in front

 0004-6256/91/051808-05$00.90  

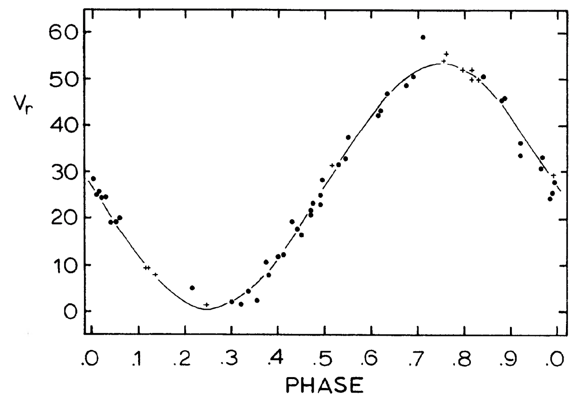


FIG. 1. Radial-velocity curve of V1149 Ori = HD 37824. Filled circles are from Balona (1987). Pluses are those of Fekel (Fekel *et al.* 1986) and the one of Bopp (1983). The solid curve represents the circular orbit in Table 1. Phases are computed with the $53\overset{d}{.}58$ orbital period and zero phase in conjunction with the K1 giant (primary star) behind.

ferent symbols. Note that the orbital period we find is identical to that found by Balona, although our uncertainty is considerably less than his. Although Balona gave only a time of periastron, we computed the corresponding time of conjunction to compare with our value.

In the process we judged two of Balona's data points (at JD 2444 235.519 and 2444 639.306) to be grossly in error and excluded them from the solution. There was a small systematic difference between Balona's and Fekel's velocities, with the former more negative by 0.8 km/s, but we did not make an adjustment for this. There was a difference also in the rms deviations: $\pm$ 2.3 km/s for Balona's velocities and $\pm$ 0.9 km/s for Fekel's.

With the rotation period now established, the $v \sin i = 11 \pm 2$ km/s from Fekel *et al.* (1986), and a radius of 15–20 $R_\odot$ typical for a K1 III Star, one can estimate the inclination of the rotational axis (and presumably also the orbital axis) to be $i = 42° \pm 12°$.

## 3. AVAILABLE PHOTOMETRY

The photometry used in our analysis is listed in Table 2. Although some of it was multibandpass, we have analyzed only that in the *V* bandpass, which gave us the most complete and nearly continuous coverage. The second column gives the number of observations (*m*) from each source. The early photometry from South Africa was published in tabular form by Lloyd Evans & Koen (1987, Tables 2 and 3). The photometry by Hall *et al.* was not published in their paper but we had access to it.

The 14 in. telescope mentioned in Table 2 is located in Winter Park, Florida. The 10 in. telescope, the one mentioned in the first section of this paper, is located on Mt. Hopkins in Arizona; the data we used, which have been published by Boyd *et al.* (1990), include the first 3 months of 1986, which Strassmeier *et al.* (1989) did not have access to. The 16 in., another automatic telescope located on Mt. Hopkins, has been described by Hall (1987). All of the new photometry mentioned in Table 2 was obtained differentially with respect to a comparison star, corrected for differential

TABLE 2. Available photometry.

| JD range 2440000+ | m | source |
|---|---|---|
| 3855 - 4974 | 64 | Lloyd Evans and Koen (1987) - table 2 |
| 4637 - 4974 | 16 | Lloyd Evans and Koen (1987) - table 3 |
| 4594 - 5394 | 45 | Hall et al. (1983) |
| 5650 - 5993 | 19 | this paper - 14-inch |
| 5701 - 6519 | 258 | this paper - 10-inch |
| 7414 - 7971 | 186 | this paper - 16-inch |

atmospheric extinction, and transformed differentially to the *UBV* system.

The South African photometry was tabulated as magnitudes. The photometry of Hall *et al.* (1983) and that obtained with the 14 in. was differential with respect to the comparison star HD 37741. Both the 10 and 16 in. automatic telescopes used HD 38309 as a comparison star. The South African photometry and that which used HD 37741 partially overlapped in time, making it possible to determine the magnitude of that comparison star empirically, namely, $V = 8\overset{m}{.}175$, with an uncertainty of about $\pm 0\overset{m}{.}01$. A recent direct measurement (Cutispoto 1991) has yielded $V = 8\overset{m}{.}20 \pm 0\overset{m}{.}01$, which is reasonably consistent. The 4th ed. of the *Catalogue of Stars Measured in the Geneva Observatory Photometric System* gives $V = 6\overset{m}{.}089$ for HD 38309. Thus we are able to specify *V* magnitudes for all of the various sets of differential photometry.

## 4. LIGHT-CURVE FITTING

Because the double-humped light-curve shape indicated at the outset that V1149 Ori often has had two major starspot groups, we used the two-spot light-curve fitting procedure devised by Hall *et al.* (1990). Each fit is characterized by seven parameters: (a) the magnitude at maximum light, (b) the rotation periods of the two spots, which can be different, presumably as a consequence of a gradient in rotation with stellar latitude, (c) epochs when the two spots are facing Earth, expressed as two Julian Dates, and (d) the light losses produced by the two spots, both expressed in magnitudes.

A fit is achieved by finding the set of seven parameters which minimizes the sum of the squares of the residuals from the computed light curve. The uncertainty of each parameter is that resulting from chi-squared analysis. The magnitude at maximum light does not necessarily correspond to a spotless hemisphere. For example, there could be polar cap or a belt of spots darkening the star within a certain latitude range but distributed uniformly in longitude. The fitting procedure used by us will measure only spotted regions which are longitudinally asymmetric.

First we divided the available photometry into 18 datasets. Most of the observing seasons were treated as one dataset. The last four observing seasons, however, had relatively generous coverage and could be divided into three datasets each. In those cases, in order that each set could define a complete stellar rotation, a few points at the end of one set were used again at the beginning of the next. The first dataset

TABLE 3. Starspot parameters.

| data set | median epoch | n | Julian date (2440000.+) | amplitude (mag.) | spot | maximum (mag.) | rms (mag.) |
|---|---|---|---|---|---|---|---|
| 1 | 1979.00 | 12 | 3873.7 ± 1.3 | 0.053 ± 0.006 | A | [6.657] | 0.011 |
| 2 | 1980.03 | 21 | 4252.0 ± 0.2 | 0.098 ± 0.003 | A | 6.657 ± 0.002 | 0.007 |
| | | | 4270.6 ± 0.5 | 0.137 ± 0.008 | B | | |
| 3 | 1981.12 | 41 | 4592.3 ± 0.2 | 0.114 ± 0.002 | B | 6.663 ± 0.001 | 0.010 |
| | | | 4677.3 ± 0.7 | 0.029 ± 0.004 | A | | |
| 4 | 1982.01 | 36 | 4967.6 ± 0.4 | 0.082 ± 0.003 | B | 6.738 ± 0.002 | 0.011 |
| | | | 4987.2 ± 0.7 | 0.058 ± 0.007 | C | | |
| 5 | 1983.04 | 15 | 5329.0 ± 0.2 | 0.108 ± 0.006 | D | 6.730 ± 0.002 | 0.006 |
| | | | 5358.8 ± 0.4 | 0.101 ± 0.003 | C | | |
| 6 | 1984.14 | 74 | 5734.7 ± 0.2 | 0.170 ± 0.003 | C | 6.678 ± 0.002 | 0.013 |
| | | | 5754.1 ± 0.2 | 0.127 ± 0.004 | D | | |
| 7 | 1984.85 | 52 | 6002.6 ± 0.1 | 0.215 ± 0.004 | C | 6.644 ± 0.002 | 0.014 |
| | | | 6018.6 ± 0.2 | 0.146 ± 0.004 | D | | |
| 8 | 1984.96 | 22 | 6056.0 ± 0.3 | 0.206 ± 0.010 | C | 6.640 ± 0.003 | 0.016 |
| | | | 6069.2 ± 0.4 | 0.164 ± 0.008 | D | | |
| 9 | 1985.15 | 32 | 6112.0 ± 0.2 | 0.231 ± 0.006 | C | 6.608 ± 0.003 | 0.018 |
| | | | 6128.0 ± 0.5 | 0.155 ± 0.009 | D | | |
| 10 | 1985.72 | 30 | 6325.9 ± 0.2 | 0.236 ± 0.004 | C | 6.633 ± 0.003 | 0.016 |
| | | | 6339.9 ± 0.3 | 0.186 ± 0.008 | D | | |
| 11 | 1985.87 | 52 | 6379.5 ± 0.2 | 0.246 ± 0.006 | C | 6.623 ± 0.003 | 0.025 |
| | | | 6394.2 ± 0.2 | 0.298 ± 0.010 | D | | |
| 12 | 1986.02 | 20 | 6432.8 ± 0.4 | 0.225 ± 0.012 | C | 6.614 ± 0.005 | 0.021 |
| | | | 6447.8 ± 0.3 | 0.261 ± 0.011 | D | | |
| 13 | 1988.86 | 46 | 7467.4 ± 0.3 | 0.098 ± 0.003 | F | 6.844 ± 0.002 | 0.012 |
| | | | 7487.3 ± 0.8 | 0.043 ± 0.005 | E | | |
| 14 | 1989.01 | 37 | 7523.5 + 1.2 | 0.093 ± 0.005 | F | 6.828 ± 0.003 | 0.017 |
| | | | 7541.2 + 1.4 | 0.043 ± 0.005 | E | | |
| 15 | 1989.16 | 34 | 7575.3 ± 0.4 | 0.128 ± 0.004 | F | 6.801 ± 0.002 | 0.013 |
| | | | 7594.6 ± 0.6 | 0.078 ± 0.007 | E | | |
| 16 | 1989.80 | 39 | 7811.7 ± 0.5 | 0.150 ± 0.008 | E | 6.794 ± 0.003 | 0.020 |
| | | | 7829.6 ± 0.8 | 0.055 ± 0.007 | F | | |
| 17 | 1989.95 | 26 | 7866.6 ± 0.3 | 0.180 ± 0.006 | E | 6.780 ± 0.004 | 0.016 |
| | | | 7887.6 ± 1.4 | 0.080 ± 0.008 | F | | |
| 18 | 1990.11 | 18 | 7923.5 ± 0.8 | 0.159 ± 0.011 | E | 6.780 ± 0.006 | 0.022 |
| | | | 7940.2 ± 2.2 | 0.046 ± 0.021 | F | | |

was quite sparse in phase coverage. Only one light minimum was apparent, and the level at light maximum was not well defined. For this one set, therefore, we used the level at light maximum found for the second dataset, one year later. This assumption may have compromised the resulting spot amplitude somewhat but probably not the epoch of its light minimum. For two sets the procedure was modified to allow for a gradual systematic brightening: $0^{m}01/100^{d}$ for dataset 2 and $0^{m}03/100^{d}$ for dataset 6.

The parameters resulting from the best fit to each of our 18 datasets are presented in Table 3. The third column is the number of individual observations in each set. (Because some points were used twice, as explained above, the sum of $n$ in this table is a little larger than the sum of $m$ in Table 1.) The identification of the two spots in each dataset (for example, A and B) is explained in the next section. The last column is the rms deviation of the individual magnitudes from the theoretical curve generated from those parameters. It ranged from $\pm 0^{m}006$ in the best case to $\pm 0^{m}025$ in the worst.

Hall *et al.* (1990) developed their procedure to unravel the photometric behavior of V478 Lyr. Because of its unfortunate rotation period, very near exactly two days, each light curve had to include data from almost ten cycles in order to achieve complete phase coverage. That made it important to know the precise rotation period for each spot, especially when the two spots had appreciably different periods. V1149 Ori, with its long rotation period, did not have this problem. The fit to each dataset, which in many cases covered only one rotation cycle, was not very sensitive to the precise value used for the rotation period of the two spots. For this reason, we effectively were spared two of the seven free parameters.

Figures 2–4 show the light curves of three of the datasets, and the corresponding theoretical curves generated by their spot parameters taken from Table 4. The first (dataset 3) covers 2.6 rotation cycles but we have let the abscissa be phase (based on a rotation period of $53^{d}6$ for both spots) because the scant number of points did not define each cycle separately. The second (dataset 6) covers almost two complete cycles, but the Julian Date abscissa allows them to be seen. The third (dataset 7) covers a little more than one cycle, but illustrates one of the light curves with a relatively large amplitude.

## 5. THE EVOLUTION OF SIX SPOTS

In Fig. 5 we plot the Julian Dates of spot minima, taken from Table 4, in a migration curve. To do this one computes phase with the ephemeris

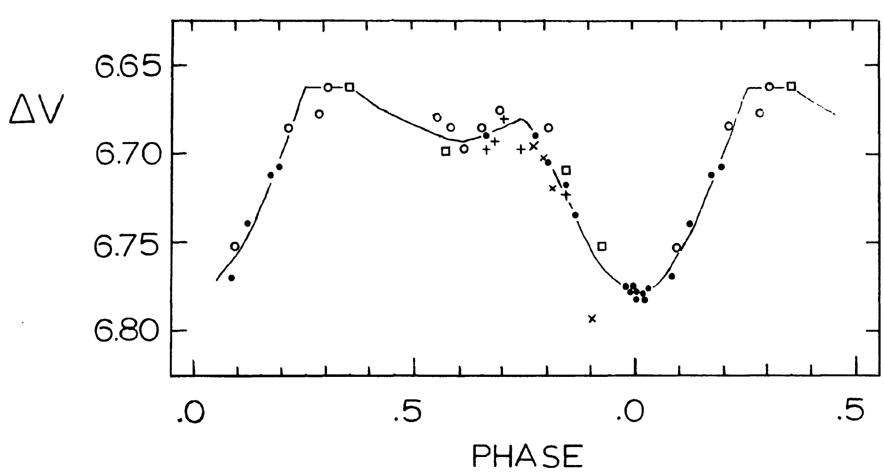


FIG. 2. The 1981.12 light curve of V1149 Ori. The ordinate is *V* magnitude. The abscissa is phase computed with a $53^{d}6$ period and zero phase corresponds to light minimum for spot B. Filled circles and pluses are from Tables 2 and 3, respectively, of Lloyd Evans & Koen (1987). Open circles, crosses, and open squares are from Dyer, Scuppernong, and Louth Observatories, respectively, presented originally in Hall *et al.* (1983). The solid curve represents the two-spot fit of dataset 3 in Table 3.

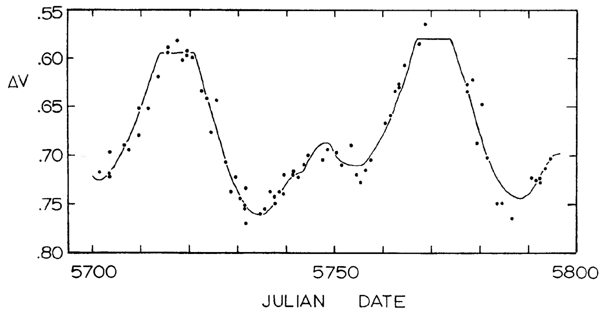


FIG. 3. The 1984.14 light curve of V1149 Ori. The ordinate is differential $V$ magnitude in the sense variable minus HD 38309. The abscissa (plus 2444 000) is Julian Date. All of the data came from the 10 in. automatic telescope. The solid curve represents the two-spot fit of dataset 6 in Table 3.

TABLE 4. Starspot rotation periods.

| Spot | Period (days) | ΔP/P (percent) |
|---|---|---|
| A | 53.56 ± 0.24 | −0.03 ± 0.44 |
| B | 53.694 ± 0.005 | +0.21 ± 0.01 |
| C | 53.60 ± 0.05 | +0.03 ± 0.10 |
| D | 53.27 ± 0.12 | −0.59 ± 0.22 |
| E | 54.24 ± 0.24 | +1.23 ± 0.44 |
| F | 52.07 ± 0.36 | −2.83 ± 0.68 |

$$\mathrm{JD(conj)} = 2444\,325.93 + 53^{\mathrm{d}}58E, \qquad (1)$$

where the initial epoch is the time of conjunction (K1 giant in front) and the period is the orbital period, both taken from Table 1. The abscissa is the cycle number $E$ and thus corresponds to time. The ordinate is the fractional part of the cycle number $\theta$. Values of $\theta(\min) = 0^{\mathrm{P}}0$ or $0^{\mathrm{P}}5$ would indicate that the spot was on the hemisphere opposite the unseen companion star or on the hemisphere facing it, respectively.

From this migration curve we have identified six spots. Each one during its lifetime maintained a constant rotation period, indicated by a line segment of constant slope in Fig. 5. The values of these six periods, which were determined by linear least squares, are given in Table 4.

The amplitudes of these six spots evolve in a continuous manner throughout their lifetimes. Some rise to a maximum and then decline to a nearly vanishingly small amplitude as they come to the end of their lives. Others are seen to rise smoothly to a maximum or fall smoothly from a maximum. The largest spot amplitude during the 11 years we studied was $0^{\mathrm{m}}3$, for spot D in 1985.9. At that epoch the overall range of variability in the light curve was also the greatest, almost $0^{\mathrm{m}}4$, because both spots had large amplitudes and were not separated very far in stellar longitude, only 100°.

## 6. DIFFERENTIAL ROTATION COEFFICIENT

The last column in Table 5 shows that the six spot rotation periods range from 1.2% slower than synchronous to 2.8% faster than synchronous, the full range thus being 4%. If we adopt a value of $0.5 \pm 0.1$ for the factor $f$ defined by Hall & Busby (1990, Fig. 2), we can estimate that $k = 0.08 \pm 0.02$ in the expression

$$P_\phi = P_{\mathrm{EQ}}/(1 - k \sin^2 \phi) \qquad (2)$$

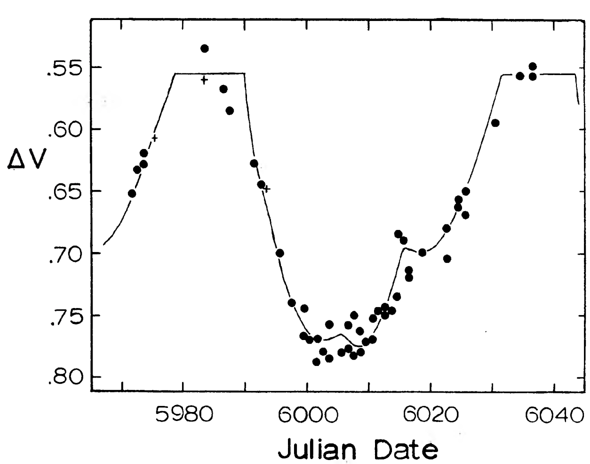


FIG. 4. The 1984.85 light curve of V1149 Ori. The ordinate is differential $V$ magnitude in the sense variable minus HD 38309. The abscissa (plus 2444 000) is Julian Date. The filled circles are from the 10 in. automatic telescope; the plusses are from Barksdale's 14 in. The solid curve represents the two-spot fit of dataset 7 in Table 3.

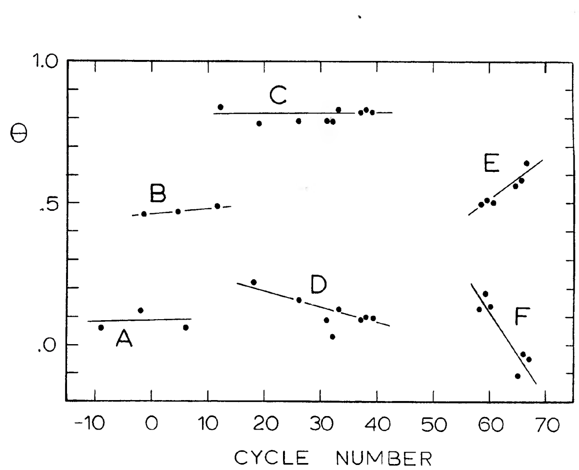


FIG. 5. Migration curve for six starspots. During each spot's lifetime, it maintained a constant rotation period, indicated by a straight-line segment. Downward slopes represent rotation faster than synchronous; upward slopes, slower.

TABLE 5. Starspot lifetimes.

| Spot | t(obsv) (yrs.) | max.ampl. (mag.) | radius (deg.) | t(calc) (yrs.) |
|---|---|---|---|---|
| A | > 2.3 | 0.098 | 14.5 | 4.6 - 12.8 |
| B | > 2.4 | 0.137 | 17.3 | 3.8 - 9.0 |
| C | 4.4 - 7.0 | 0.246 | 23.0 | 2.9 - 5.1 |
| D | 3.2 - 5.7 | 0.298 | 25.3 | 2.6 - 4.2 |
| E | > 1.5 | 0.180 | 19.8 | 3.3 - 6.8 |
| F | > 1.5 | 0.128 | 16.7 | 3.9 - 9.6 |

commonly used to describe differential rotation as a function of stellar latitude $\phi$. In such an expression $k = 0.19$ for the Sun.

Hall [1991, Eq. (2)] estimated $k$ in this way for a sample of 85 spotted stars, both single and binary, and found the following empirical relation:

$$\log k = -2.02 + 0.79 \log P(\text{rot}) - 0.42F, \qquad (3)$$
$$\pm 0.12 \pm 0.06 \qquad \pm 0.16$$

where $P(\text{rot})$ is in days and $F$ is Roche-lobe-filling fraction. If we assume a canonical value for the radius of a K1 III star and masses representative of long-period RS CVn-type binaries, then $F$ should be around 0.5 for V1149 Ori. With $P = 53^d58$, Eq. (3) would have $k = 0.14 \pm 0.06$. Thus one can see that V1149 Ori (for which we found $k = 0.08 \pm 0.02$) is consistent with that relation.

## 7. STARSPOT LIFETIMES

From the length of the line segments in Fig. 5, we can estimate the lifetimes of the six spots. These are entered in Table 5 as $t$(obsv). Because we did not witness the birth of spots A and B nor the demise of spots E and F, we can estimate only their minimum lifetimes.

Hall & Busby [1990, Eq. (5)] derived a formula for estimating the time for a spotted region to be disrupted by the shear of differential rotation. They found, moreover, that observed spot lifetimes were equal to these calculated disruption times, at least for spots larger than about 15° or 20° in radius. The input parameters in their formula are all available for V1149 Ori. The first is the orbital period: $P = 53^d6$. The second is the differential rotation coefficient: $k = 0.08$. The third is the maximum spot radius, which Hall and Busby show can be estimated from the maximum amplitude of the starspot wave. The maximum amplitudes, taken from Table 3, and the corresponding radii are entered in Table 5. The disruption lifetimes for our six spots, calculated in this way, are entered as $t$(calc) in the final column of Table 5. They are given as a range, because $t$(calc) depends on the latitude of the spot, which is not known.

For spots C and D, the two for which $t$(obsv) was not just a lower limit, the agreement between $t$(obsv) and $t$(calc) is perfect. Thus, two more points could be added to strengthen the finding made by Hall & Busby (1990), seen in the last figure of their paper.

## 8. VARIABILITY OF LIGHT MAXIMUM

Judging from the values in the next-to-last column of Table 3, the magnitude at maximum has varied over quite a range, $0^m23$ in $V$. The changes have been gradual and the occurrence of two minima (around 1982 and 1988) suggests an ~6 yr timescale for this behavior, although it would be premature to characterize it as cyclical.

It may be important that the hemisphere which we have presumed to be least spotted reached its maximum brightness during the years when the degree of total spottedness (the sum of the light losses produced by the two spots) was greatest.

The 16 in. APT was obtained with NSF Grant No. AST-84-14594 to D.S.H., and its continued operation and data analysis are supported by NASA Grant No. NAG-8-111 to Tennessee State University. We are grateful to B. W. Bopp for placing his one radial-velocity measurement at our disposal and to G. Cutispoto for providing comparison star magnitudes which we had overlooked.

## REFERENCES

Balona, L. A. 1987, SAAO Circ., 11, 1
Bopp, B. W. 1983, private communication
Boyd, L. J., Genet, R. M., Hall, D. S., Busby, M. R., and Henry, G. W. 1990, IAPPP Comm., 42, 54
Cutispoto, G. 1991, private communication
Fekel, F. C., Moffett, T. J., and Henry, G. W. 1986, ApJS, 60, 551
Hall, D. S. 1987, in Automatic Small Telescopes, edited by D. S. Hayes and R. M. Genet (Fairborn, Mesa, AZ), p. 65
Hall, D. S. 1991, in The Sun and Cool Stars: Activity, Magnetism, and Dynamos, edited by I. Tuominen (Springer, Berlin), p. 353
Hall, D. S., and Busby, M. R. 1990, in Active Close Binaries, edited by C. Ibanoglu (Kluwer, Dordrecht), p. 377
Hall, D. S., Henry, G. W., Louth, H., and Renner, T. R. 1983, IBVS No. 2409
Hall, D. S., Henry, G. W., and Sowell, J. R. 1990, AJ, 99, 396
Lloyd Evans, T., and Koen, M. C. J. 1987, SAAO Circ., 11, 21
Strassmeier, K. G., Hall, D. S., Boyd, L. J., and Genet, R. M. 1989, ApJS, 61, 141
Strassmeier, K. G., Hall, D. S., Zeilik, M., Nelson, E. R., Eker, Z., and Fekel, F. C. 1988, A&AS, 72, 291