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Time-series photometric spot modeling

II. Fifteen years of photometry of the bright RS CVn binary HR 7275

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Abstract. We present a time-dependent spot modeling analysis of 15 consecutive years of V-band photometry of the long-period ($P_{\rm orb}$ = 28.6 days) RS CVn binary HR 7275. This baseline in time is one of the longest, uninterrupted intervals a spotted star has been observed. The spot modeling analysis yields a total of 20 different spots throughout the time span of our observations. The distribution of the observed spot migration rates is consistent with solar-type differential rotation and suggests a lower limit of the differential-rotation coefficient of 0.022±0.004. The observed, maximum lifetime of a single spot (or spot group) is 4.5 years, the minimum lifetime is approximately one year, but an average spot lives for 2.2 years. If we assume that the mechanical shear by differential rotation sets the upper limit to the spot lifetime, the observed maximum lifetime in turn sets an upper limit to the differential-rotation coefficient, namely 0.04±0.01. This would be differential rotation just 5 to 8 times less than the solar value and one of the strongest among active binaries. We found no conclusive evidence for the existence of a periodic phenomenon that could be attributed to a stellar magnetic cycle.

Key words: stars: activity – stars: atmospheres – stars: late-type – stars: HR 7275 – stars: variables: other

1. Introduction

A significant part of the past progress in the study of starspots on late-type stars has come from the analysis of broad-band light curves (for recent reviews on starspot photometry see, e.g., Hall 1991; Eaton 1992; Strassmeier 1992; Guinan & Gimenez 1993). The "starspot hypothesis" is that a spotted star's periodic light variation results from an inhomogeneous surface temperature distribution and is modulated with the stellar rotation period. Long-term variations of light curves might tell us the existence and length of a spot cycle similar to the solar 11-year cycle. A major advent in the history of starspot photometry was the dedication of the first, fully automatic photoelectric telescope (APT) to the study of spotted RS CVn binaries and related stars in 1983. In this paper we will investigate the bright RS CVn binary HR 7275 which has been observed with such APTs since they began to operate.

HR 7275 (V1762 Cyg, HD 179094) is a 28.6-day spectroscopic binary with a K1III-IV primary and an unseen secondary component (Young 1944; Eker 1989; Bopp et al. 1989). The star exhibits very strong Ca II H and K emission lines typical of RS CVn binaries (Joy & Wilson 1949; Bidelman 1964; Young & Koniges 1977; Bopp 1984; Fekel et al. 1986). Early photometry by Herbst (1973) revealed the light variability of this system. This was confirmed by Fried et al. (1982), who also showed the star to have a highly variable light curve, with changes on a time scale of one orbital period or even less. Further data, covering the years 1984 through 1986, were presented by Strassmeier et al. (1989). From data up to 1985, Seeds & Nations (1986) suggested a cyclic behavior of the changes in the shape of the light curve with a period of 5 years which, however, still needs to be confirmed. Preliminary spot modeling by Zeilik et al. (1984) and Nations & Seeds (1986) suggests that the variations in amplitude are due to changes in both area and the position of the cool starspots. Thus, HR 7275 is a good candidate for the time-series spot modeling technique developed by Strassmeier & Bopp (1992; hereafter called Paper I).

2. Time-series spot modeling

Paper I presented our new modeling technique and a parameter study of the involved free parameters of a spot model with rectangular spots. For details we refer the reader to this paper. Basically, we apply a least-squares trial-and-error algorithm to several consecutive light curves of a rotating star within a given parameter space. Every point in the light curve is computed from a disk integration of a model star where a simple Planckian energy distribution is used to convert effective temperature into

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Table 1. V-band photometry of HR 7275

Year	data set	n_{obs}	$< V >$	ΔV_{max}	P_{phtm}
1971.50	Herbst	19	5.840	0.058	...
1978.76	Fried et al.	88	5.920	0.158	29.407
1979.71	Fried et al.	43	5.942	0.191	28.270
1980.65	Fried et al.	60	5.914	0.230	27.797
1980.82	IAU file 121	18	5.914	0.230	...
1981.60	IAU file 273	78	5.894	0.276	28.671
1982.64	IAU file 273	81	5.903	0.145	30.335
1983.66	IAU file 273	146	5.922	0.171	27.652
1983.85	Phoenix APT	36	5.918	0.173	26.327
1984.50	IAU file 147	40	5.870	0.164	26.771
1984.52	IAU file 273	154	5.883	0.164	27.070
1984.53	Phoenix APT	91	5.885	0.164	27.722
1985.53	Phoenix APT	158	5.887	0.224	28.789
1985.55	IAU file 273	6	...	...	...
1985.62	Reglero et al.	5	...	...	...
1986.49	Phoenix APT	42	5.902	0.116	28.180
1987.55	Phoenix APT	46	5.993	0.125	28.237
1988.61	VU-TSU APT	99	5.964	0.115	27.945
1989.54	VU-TSU APT	80	5.938	0.177	28.316
1990.55	VU-TSU APT	47	5.912	0.153	28.034
1991.32	VU-TSU APT	64	5.938	0.213	28.418
1992.56	VU-TSU APT	81	5.922	0.158	27.985

Table 2. Observers contributing new photometry

Observer Name	Observatory Location	Telescope Aperture (cm)
Barksdale, William S.	Florida	35
Brooks, Peter A.	Pennsylvania	31
Engelbrektson, Sune	New York	27
Fried, Robert E.	Arizona	60
Fortier, George L.	Quebec	31
Grim, Bruce S.	Utah	40
Landis, Howard J.	Georgia	20
Lines, Richard D.	Arizona	50
Louth, Howard P.	Washington	27
Lovell, Larry P.	Ohio	25
Nielsen, Paul	Delaware	10
Poe, Clinton H.	Tennessee	60
Reisenweber, Robert C.	Pennsylvania	20
Renner, Thomas R.	Wisconsin	25
Rogers, Charles W.	Oklahoma	35
Shervais, Steve	Virginia	15
Slauson, Douglas M.	Iowa	20
Stelzer, Harold J.	Illinois	35
Troeger, Jack C.	Iowa	20
Wasson, Norman R.	California	20
Wiggins, Pat	Utah	35
Zeigler, Kenneth W.	Arizona	27

flux. Surface temperatures are obtained from the variations of $V-I$ color curves and are adopted to be constant throughout the rest of the V observations. Because of the relatively high inclination of the rotation axis of HR 7275 ($\approx 70°$) we assumed the lower boundary for each spot to be at the stellar equator. Time-dependence of a spot's variations is introduced in form of a solar-type differential rotation law $\Omega = \Omega_0 + \Omega_2 \sin^2 \theta$, as well as cyclic behavior of the spot area in analogy to the solar 11-year cycle. Modern computers then allow to search through the entire multi-dimensional parameter space and find all physically reasonable solutions. While we cannot claim that the spot solutions of the individual light curves are mathematically unique, we are able to separate periodic effects – like differential rotation or waxing and waning of particular spots – from stochastic effects that are presumably unrelated to a magnetic cycle.

3. Observations

In this paper we analyze all photometry of HR 7275 available and known to us, both published and not yet published. The earliest was the V-band photometry of Herbst (1973). The BV photometry discussed by Fried et al. (1982) is file no. 87 in the Archive for Unpublished Observations of Variable Stars (Breger 1985). The VRI photometry discussed by Poe & Eaton (1985) is in file no. 121 of that same archive. Some 1984 $VBRI$ photometry is in Archive file no. 147 (Breger 1988). Four years of UBV photometry obtained with the Phoenix 25-cm automatic photoelectric telescope (APT) on Mt. Hopkins in Arizona was published by Boyd et al. (1990). A subset of those same data had been analyzed by Strassmeier et al. (1989). A small amount of all-sky $uvby$ photometry was published by Reglero et al. (1987). Five years of BV photometry has been obtained with the Vanderbilt–Tennessee State 40-cm APT also on Mt. Hopkins. Finally, we have available the not yet published V-band photometry from the 22 other observers listed in Table 2, most of it in 1982, 1983, and 1984. A subset of these data had been discussed but not published by Zeilik et al. (1984). The complete set has been sent to the Archive for Unpublished Observations of Variable Stars, where it is available as file no. 273.

With the exception of the Reglero et al. (1987) data, all photometry presented in this paper was obtained differentially with HR 7229 = HD 177483 as the comparison star and 51 Dra = HR 7251 = HD 178207 as the check star, corrected for differential atmospheric extinction, and transformed in a standard fashion to the Johnson UBV system. Because the available data set is far more complete in the V bandpass and because we need good continuous phase coverage to investigate the complex time behavior of the starspot evolution in HR 7275, we restricted subsequent analysis in this paper to the V bandpass alone. We converted differential magnitudes to V magnitudes by adopting $V = 6.31$ mag for the comparison star HR 7229 (Nicolet 1978). Altogether we have 1482 V magnitudes to work with, each one actually a mean of generally three individual interpolations between the variable and the comparison star. Of these, 744 come from the two APT's, operation of which were discussed critically most recently by Hall & Henry (1993a).

Table 1 is a summary of this available photometry, where n_{obs} is the number of V magnitudes, $< V >$ is the mean V brightness, ΔV_{max} is the maximum light curve amplitude

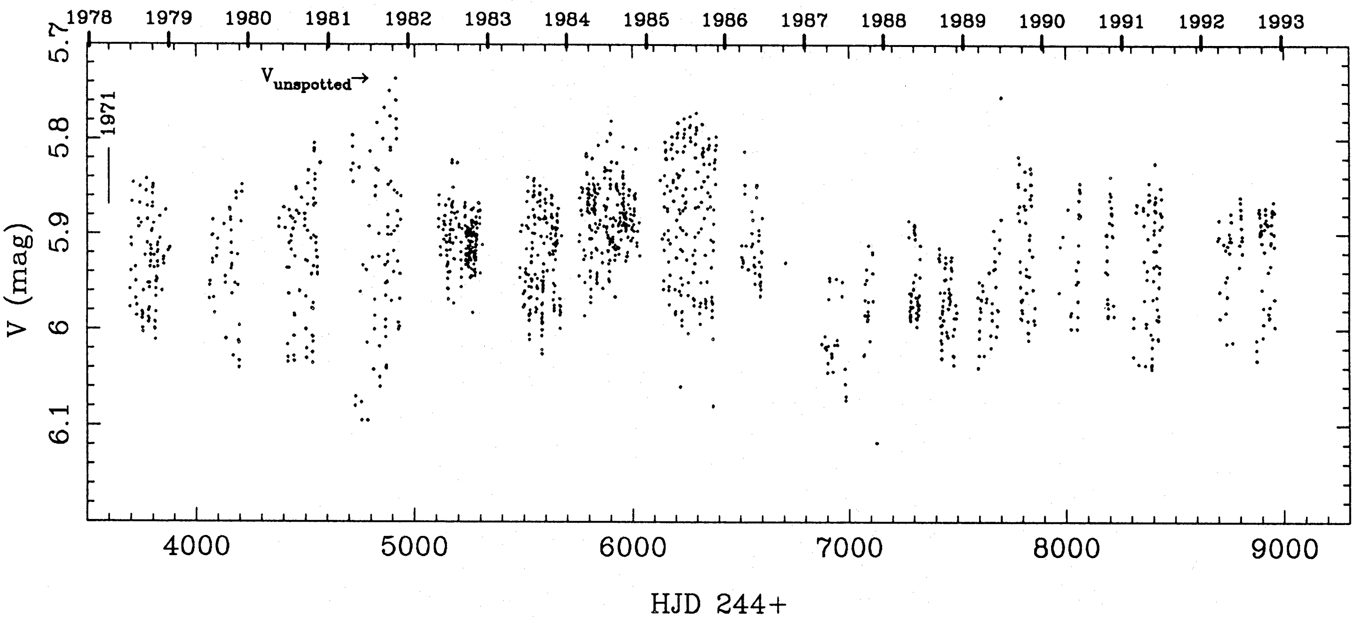

Fig. 1. Summary of the light variations of HR 7275 in the years 1978 through 1992. The star was brightest in 1981 and the adopted unspotted light level is marked. Note that the star was also dimmest in 1981 and showed then the largest amplitude ever observed for HR 7275 (≈ 0.3 mag). Also indicated is the magnitude range of the early observations of Herbst (1973) in 1971

in magnitudes, and P_{phtm} is the apparent photometric period in days, as explained in Sect. 4.3. Phase throughout this paper, however, is always orbital phase reckoned from the orbital ephemeris of Eker (1989)

$$HJD = 2,442,479.214 + 28.5895 \times E, \quad (1)$$

where the initial epoch is a time of conjunction when the K star is in front of the (unseen) secondary. Data from different sources were treated separately in Table 1, even when they were from virtually the same epoch, to allow for the possibility that there might be significant systematic differences among them. No such differences were apparent, however, especially with respect to such quantities as $< V >$ or ΔV_{max}.

4. Results and discussion

4.1. The unspotted brightness

Figure 1 shows HR 7275 at its brightest level with a peak magnitude of V_{unsp} = 5.736±0.005 mag at the end of 1981, which we assume to be the unspotted brightness of the star. Knowledge of the true unspotted brightness is essential for light curve modeling because it controls the spot area and temperature. In this paper we assume a polar spot of variable size to adjust the different seasonal light curve maxima. This is essentially a technicality because we could have also adopted a variable background spottedness (cf. Eaton & Hall 1979) but the polar-spot picture is supported from Doppler-imaging results of other RS CVn binaries of similar spectral type (cf. Vogt 1988; Strassmeier et al. 1991). Rodonó et al. (1986) assumed all the light loss is due to two spots and got high spot latitudes as a result. To the contrary Dorren & Guinan (1990) argued that, in the case

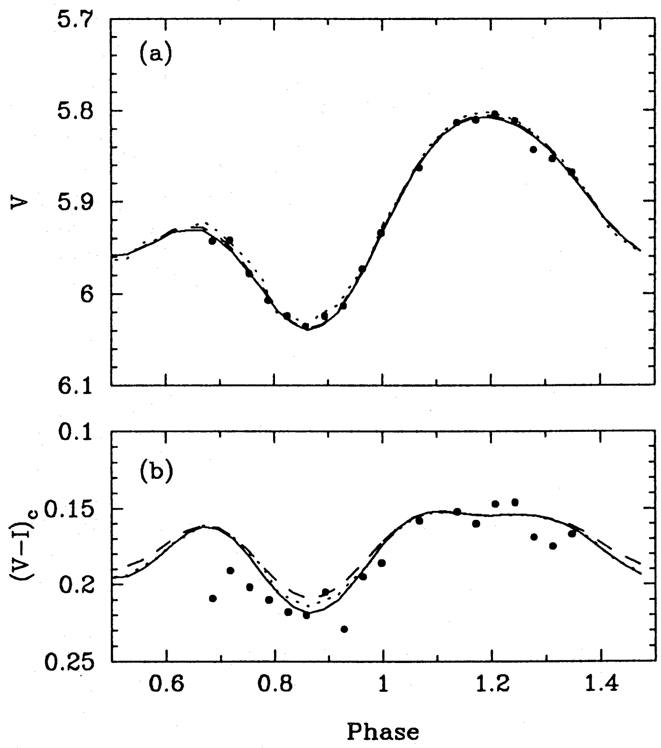

Fig. 2. V and $V-I$ light curves of HR 7275 from late 1980. The dots are the Kitt Peak data of J. A. Eaton (IAU Comm. 27, File 121). The lines are spot model fits with spot temperatures of 800 K (full line), 1000 K (dotted line), and 1200 K (dashed line). The $V-I$ amplitude of ≈ 0.07 mag at around phase 0.9 is best reproduced with a temperature difference (photosphere minus spot) of 800 K. Note that the minimum at phase ≈ 0.5 may not be real because of a lack of data at this particular phase

of the RS CVn binary V711 Tau, a variable facular contribution to its continuum brightness is the main cause for the long-term variations. Although the observational evidence for a relation between continuum brightness variations and magnetic activity cycles is strong, but probably not yet conclusive, understanding of its underlying physical mechanism is still in its infant stages (Applegate 1992).

4.2. The spot temperature

The only VRI data of HR 7275 are the Kitt Peak data of Poe & Eaton (1985). These authors already performed a spot model analysis on these data and found two high-latitude spots covering ≈9 % of the surface and being 1200 K cooler than the photosphere. However, their light curve fit produced a peak magnitude brighter than the observed one by 0.07 mag. The reason for this discrepancy was that their adopted unspotted brightness of 5.84 mag was too faint by 0.1 mag and, as was pointed out by the authors, made the derived spot temperature probably too cool.

Figure 2 plots the Poe & Eaton data and our new spot model fits. The observed $V - I$ amplitude of ≈0.07 mag at around phase 0.9 is best reproduced with spots having a temperature difference (photosphere minus spot) of 800±200 K, instead of the 1200 K obtained by Poe & Eaton. The spot parameters for the fit in Fig. 2 are listed in Table 3. We adopted a stellar surface temperature of 4820 K from the spectral type - temperature calibration of Bell & Gustafsson (1989) and an inclination of the rotation axis of 70°. The relatively high inclination was adopted on the basis that the unseen secondary companion is a main sequence star and that no eclipses are observed (Eker 1989). Limb darkening coefficients were taken from Al-Naimiy (1978) to be 0.75, 0.61, and 0.50 for V, R, and I, respectively.

Table 3. Spot model for 1980.8

Spot	ΔT (K)	longitude (deg)	latitude (deg)	area (%)
pole	800	...	57	8.0
A	800	8	12	3.8
B	800	238	22	5.6

4.3. The seasonal photometric periods

Scharlemann (1982) showed that the forces in a binary system, that act to achieve synchronism between surface rotation and orbital revolution, are not strong enough to suppress differential (surface) rotation. These calculations supported the suggestion of Hall (1972) that there is a co-rotating latitude at which the rotation is synchronized to the orbital motion. Thus we can interpret a particular photometric period of a spotted star as the rotation period at the latitude of the spot that causes the light modulations. If we assume solar-like differential rotation, i.e. the polar regions rotate slower than the equatorial regions, then a photometric period longer than the orbital period would indicate a spot latitude above the co-rotation latitude and vice versa.

Table 1 lists the seasonal photometric periods of HR 7275. These periods are derived from fits of sinusoids to the seasonal data by minimizing the squares of the residuals and have typical errors of 0.01 days. The range of these periods spans from 8 % slower than $P_{\rm orb}$ in 1983 to 7 % faster than $P_{\rm orb}$ in 1982, with a mean value of 28.241±1.037 days between 1978 and 1992. However, the light curve shape of HR 7275 deviates from a sinusoid most of the time and this introduces significant uncertainty. In Sect. 4.5 we make use of the migration rates of individual spots instead in order to determine the photometric periods more precisely. As we will show, an average rotation period of 28.3085 days with a standard deviation of 0.1835 days can be obtained. This is rotation 1.0 % slower than the orbital period. The corresponding average spot migration period from $P_{\rm migr}^{-1} = P_{\rm phtm}^{-1} - P_{\rm orb}^{-1}$ is 8 years. Thus the rotation of HR 7275 is synchronized to the orbital revolution and the spots reside either above *or* below the co-rotation latitude depending upon the (unknown) sign of the differential rotation coefficient (see Sect. 4.5). Another interpretation is that the spots are evenly distributed in latitude but the orbital and rotational motions are not synchronized at any latitude.

4.4. Time-series modeling

The individual light curves and the fits from our modeling are shown in Fig. 3. Each observing season was treated as a separate data set and the modeling results are plotted in time steps of one rotational cycle in Fig. 4. The changing maximum light levels for each observing season were accounted for with varying the size of the polar spot. The long seasonal gaps in the data of around 100 days make it virtually impossible to follow spot variations on a time scale of the order of one year and a close multiple thereof. Also, for some of the seasons we had significant data gaps (e.g. in 1990) so for them the data were split into two parts and again treated separately. In the following we discuss the light curves for each consecutive observing season and point out some peculiarities in the light curve shapes.

Season 1978. The light curve shape appeared slightly double humped, with a broad minimum at phase 0.6 and a smaller and variable secondary minimum around phase 0.0. The smaller minimum became increasingly deeper and is modeled by an increase of the separation between the two spots that cause the two minima.

Season 1979. The observations in 1979 commenced about 200 days after the last observation in 1978. This large gap prevents a meaningful continuation of the model integration. The observations show now just one (asymmetric) minimum at phase 0.0 and a maximum at phase 0.6. This indicates a major spot re-arrangement on the stellar surface.

Season 1980. Again there are two minima in the light curve, well separated in early 1980. By the end of the observing season the separation of approximately 0.4 phases has vanished and one deep, but asymmetric, minimum remained. We are modeling this

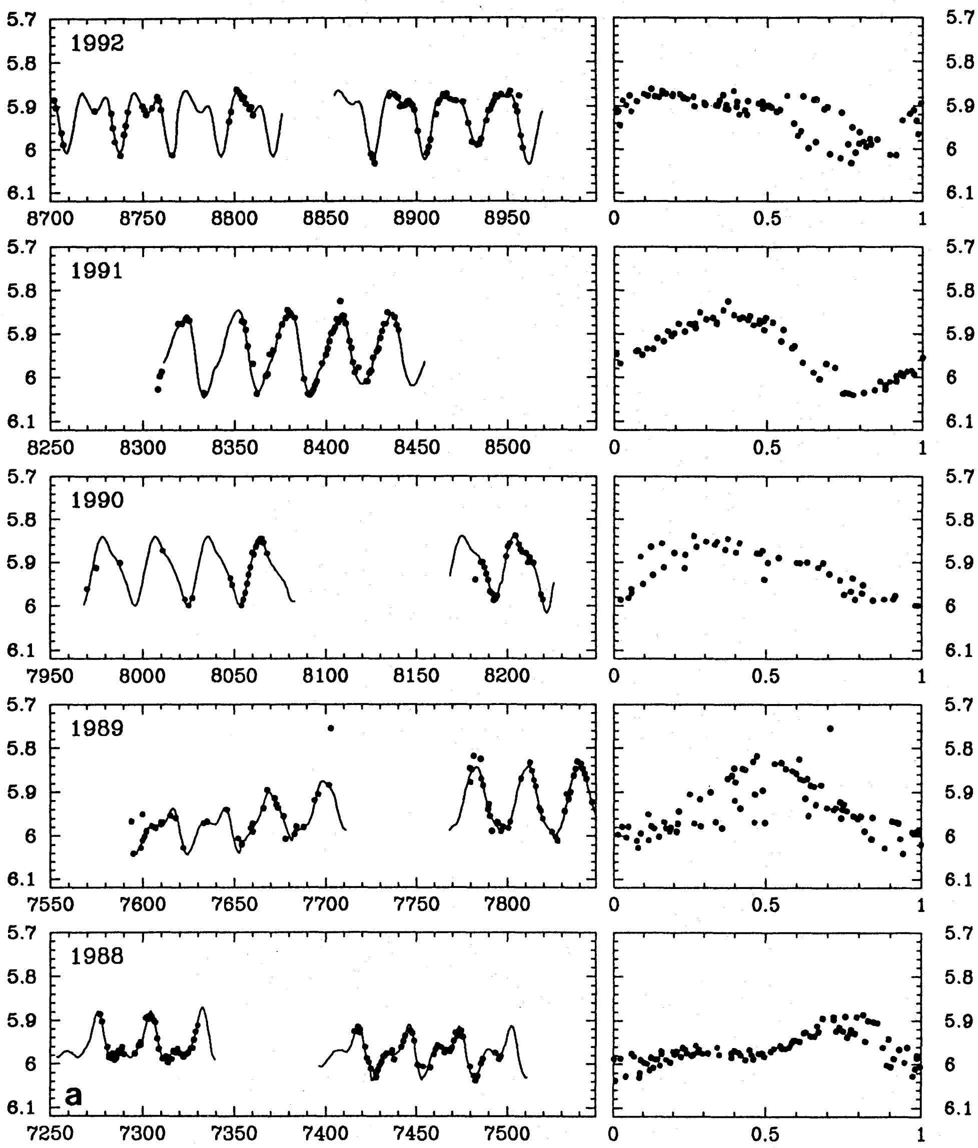

Fig. 3. a–c. Seasonal V-band light curves for the years 1992 through 1978 and our spot-modeling fits. The left panels show the data versus heliocentric Julian date (2,440,000+) and the right panels are the phased light curves with the ephemeris of Eq. (1). The full line in each Julian-date panel is the fit with a spot model as explained in the text

change with two spots of quite different migration rates and a slight increase of the size of the bigger spot.

Season 1981. The data in 1980 already indicated an increasing amplitude towards the end of 1980 and obviously this trend continued throughout the seasonal gap and the star showed the largest ever observed light variations by mid 1981. By the end of 1981 the maximum light level reached the previously adopted unspotted magnitude.

Season 1982. Quite surprising, the light curve amplitude in 1982 was down to almost zero at JD 2445250 and remained so for almost two consecutive rotations. The V-light level at this time was 5.90 mag which is fainter by 0.16 mag as compared to the end of the previous season. The big spots must have faded away during the seasonal observing gap of about 120 days.

Season 1983. As already indicated at the end of the previous season the amplitude again increased and was ≈0.1 mag throughout 1983.

Season 1984. In this season we see almost the opposite behavior than in 1980. The amplitude of the dominating minimum becomes smaller towards the end of the season while the separation to the other, smaller, minimum becomes larger. We model these variations with three spots of which two of them experiencing a change in the migration rate and the originally larger spot changes its size by almost a factor of three. The other spots remained constant.

Season 1985. Two major spots of similar migration speed dominate the light curves in 1985. The bigger one shows a first increase and then decrease of its size by about 30 % while the other spot remained more or less constant. From about JD 2446200 on we invoked a third spot to account for the triangle-shaped maximum and minimum. By the end of the season this spot had increased its size by about a factor of five.

Season 1986. Only sparse data were available for this season. Nevertheless we can reconstruct three consecutive rotations that show a very different light curve shape than in the previous

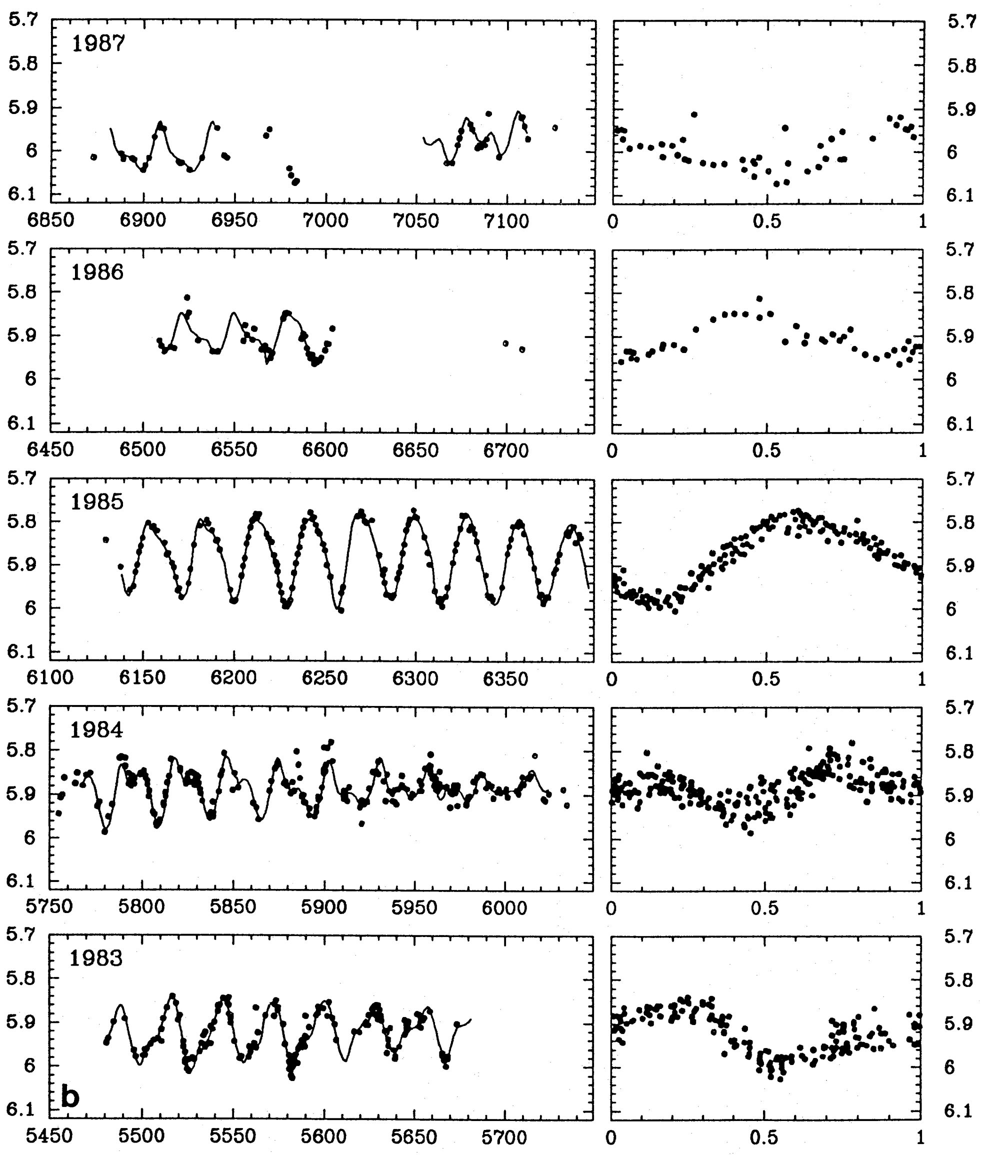

Fig. 3. (continued)

season. Also the overall brightness of 5.84 mag is 0.06 mag fainter as compared to 1985.

Season 1987. This season's light curves are dominated by the low, overall brightness: V_{max} = 5.92 mag and V_{min} = 6.08 mag, the faintest appearance of HR 7275 ever observed.

Season 1988. The light curve shape appeared very similar to the one in the previous season but the overall light level increased to 5.88 mag at the beginning of the season and slightly decreased by 0.040 mag until the end of our data coverage.

Season 1989. A continuous increase of the brightness at light curve maximum is seen in the first four consecutive rotations. Additionally, the V-amplitude increased by a factor of two within 200 days ($\approx$ 7 stellar rotations) from 0.1 to 0.2 mag. This is reflected as large scatter in the phased "seasonal" light curve in Fig. 3.

Season 1990. Although there is just one broad light curve minimum our spot modeling indicates at least two spots. One of them becoming increasingly larger and by the end of the season the light curve shape even allowed for a fourth spot, though very small and probably not significant.

Season 1991. The complicated triangle-like shape of the light curve requires a third spot to fully reproduce its variations.

Season 1992. At the beginning of the season the light curve shows a classical double-humped shape with a deep and a shallow minimum. By the end of the season, approximately 8 stellar rotations later, the light curve had changed to a single humped shape. This is nicely modeled by two different migration rates for the two spots.

4.5. Evolution of the starspots on HR 7275

An interesting result from Fig. 3 is that most spots can change their size and/or position on the stellar surface from one rotational cycle to the next. Actually, for some cases at least, the variability time scale might be even shorter because we see *significant* changes of the light curve shape in consecutive rotations (e.g. in 1989). Moreover, most of the time there is more than

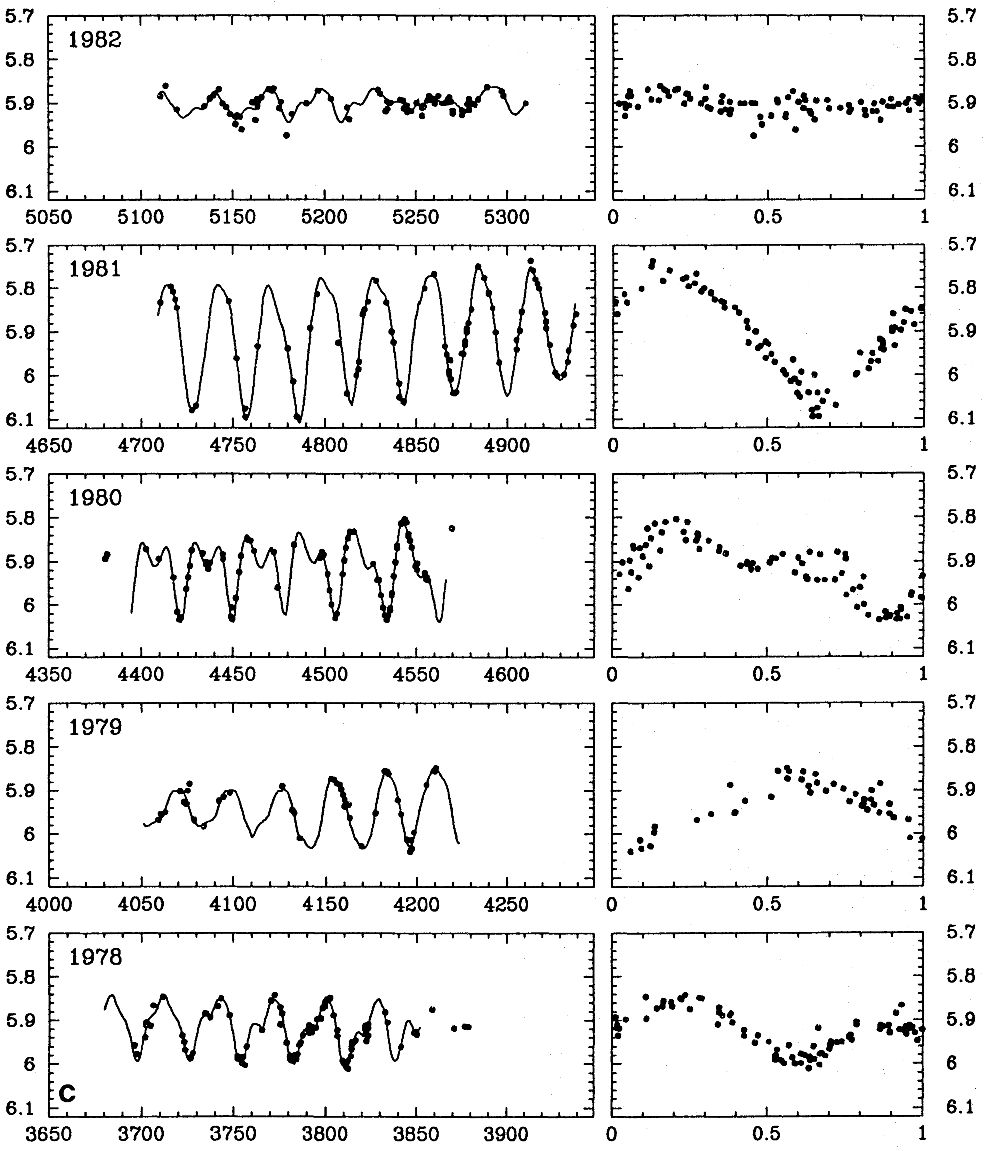

Fig. 3. (continued)

one spot on the visible surface of HR 7275 and separating the effects of the individual spots from the combined light in a time series is not straigthforward and not unambiguous. Thus the determination of a spot's approximate *lifetime* will help to separate these effects and also supplies an important quantity for a starspot theory based on dynamo action. For reasons of simplicity we furtherin assume that all spots on HR 7275 have *constant* migration rates throughout their lifetime, i.e. a spot's mean longitude shall change only linearly with time and thus produce a straight line in the stellar longitude versus time diagram in Fig. 4. In other words, we neglect latitudinal spot migration that, in the presence of differential rotation, would otherwise produce a more complicated migration curve and the identification of a spot's presence would be even more ambiguous. This is not an unreasonable assumption because, afterall, it is only the loci of sunspots which define latitude drift – an individual sunspot does not migrate in latitude throughout its lifetime.

We identify 20 different spots on HR 7275 during our fifteen years of observation (Fig. 4a). Table 5 is a list of the parameters of the individual spots. The first column identifies the spot (a, b, c etc.) and the second column lists the number of spot "points" available. The other columns are the rotation periods $P_{\rm rot}$ determined from a linear least-squares fit of the longitudinal migration in days (see Fig. 4a), the individual spot lifetimes $\tau_{\rm spot}$ in days, and the *maximum* area $A_{\rm spot}$ during a spot's lifetime in per cent of the entire sphere. We again emphasize that the linear fits in Fig. 4a are not a physical interpretation of the spot migration but are used to estimate a mean rotation period over the lifetime of a particular spot in absense of a concrete starspot theory.

Figure 5 is a plot of spot lifetime against maximum spot area of the 20 spots seen on HR 7275 over the past 15 years. For some of the spots only lower limits of their lifetimes are available and these are marked. Either there is no clear correlation between lifetime and area of a starspot on HR 7275 or

Table 4. Spot models for 1978 through 1992

Mid-time	Pole	Spot 1			Spot 2			Spot 3			Spot 4		
	area	l_1	l_2	area	l_1	l_2	area	l_1	l_2	area	l_1	l_2	area
HJD244+	(%)	(°)		(%)	(°)		(%)	(°)		(%)	(°)		(%)
3710.	6.680	18	78	4.660	135	177	1.995	270	320	2.542	...	...	...
3750.	6.680	22	90	5.144	135	177	1.510	240	320	4.067	...	...	...
3785.	6.680	22	90	5.144	135	177	1.510	240	320	4.067	...	...	...
3820.	6.680	20	95	5.520	135	175	1.624	240	320	4.067	...	...	...
3865.	6.680	42	102	4.660	140	180	1.624	245	325	4.067	...	...	...
4075.	16.498	155	180	1.467	255	285	1.761	...	...	...	...	...	...
4115.	16.498	155	180	1.467	255	290	2.431	...	...	...	...	...	...
4165.	13.994	155	195	3.107	248	285	2.799	...	...	...	...	...	...
4200.	11.665	160	190	1.695	238	285	4.019	...	...	...	...	...	...
4415.	10.068	271	313	4.977	93	127	2.253	...	...	...	...	...	...
4447.	9.042	277	315	4.959	85	125	2.651	...	...	...	...	...	...
4475.	8.548	280	320	4.933	78	122	2.916	...	...	...	...	...	...
4505.	8.066	285	335	5.524	78	122	2.916	...	...	...	...	...	...
4540.	6.699	288	341	6.024	60	115	4.003	...	...	...	...	...	...
4720.	6.680	303	345	3.750	20	74	5.865	95	120	1.244	...	...	...
4755.	6.680	310	353	3.839	19	74	5.973	120	140	0.766	...	...	...
4793.	6.680	320	355	3.125	12	65	5.756	120	150	2.083	...	...	...
4830.	4.311	315	350	3.125	20	70	6.030	138	158	1.085	...	...	...
4865.	3.015	302	343	3.660	20	73	6.518	125	153	1.137	...	...	...
4895.	0.	303	348	4.562	25	75	6.941	130	155	1.736	...	...	...
4930.	0.	298	350	5.523	30	81	5.783	130	155	1.736	...	...	...
5115.	13.432	300	350	1.206	63	90	1.465	153	172	0.903	...	...	...
5145.	13.432	300	350	1.206	63	90	1.465	153	172	0.903	...	...	...
5175.	13.432	300	345	0.978	70	100	1.761	150	165	0.362	...	...	...
5205.	13.432	300	345	0.978	70	100	1.761	150	165	0.362	...	...	...
5235.	13.432	300	360	1.304	75	95	0.766	150	165	0.362	...	...	...
5265.	13.432	300	360	1.304	75	95	0.766	...	...	...	220	240	0.719
5297.	13.432	310	370	1.447	...	...	...	...	...	...	240	260	0.719
5485.	10.570	53	92	2.870	245	285	2.348	340	380	2.260	140	155	0.609
5515.	10.570	53	92	3.482	258	298	1.991	340	375	1.977	140	150	0.241
5545.	11.112	52	90	2.951	267	307	1.900	340	375	1.742	135	150	0.362
5575.	11.665	60	100	3.107	282	318	1.545	350	375	1.245	148	162	0.437
5605.	10.570	75	110	2.576	282	310	1.520	10	45	1.977	160	175	0.539
5645.	10.470	87	122	2.576	275	305	1.761	10	45	1.821	170	185	0.609
5665.	10.570	90	125	2.718	282	310	1.582	20	53	1.864	190	205	0.609
5765.	6.699	58	105	4.108	265	305	2.348	150	180	2.083	...	...	...
5795.	6.699	61	107	4.021	265	295	1.827	150	180	1.761	...	...	...
5825.	6.699	63	106	3.426	265	295	1.761	145	181	2.113	...	...	...
5855.	6.699	65	107	3.429	265	300	2.131	150	186	2.270	...	...	...
5885.	6.699	67	107	3.187	265	305	2.608	155	192	2.569	...	...	...
5915.	6.699	70	108	2.559	265	305	2.693	160	197	2.569	...	...	...
5945.	6.699	80	118	2.314	280	330	2.935	170	210	2.348	...	...	...
5975.	9.042	80	116	2.192	305	335	1.425	170	200	1.288	240	260	0.950
6005.	9.042	82	115	1.492	305	335	1.425	170	200	1.425	240	260	0.950
6135.	4.685	175	220	3.585	250	290	2.778	102	116	0.569	350	385	1.663
6165.	4.685	167	217	4.464	260	300	2.778	...	...	...	10	45	1.258
6195.	4.685	173	223	4.556	260	300	2.608	102	116	0.569	350	370	0.904
6225.	4.685	177	228	4.740	260	297	2.413	110	130	0.812	350	370	0.718
6255.	4.685	180	230	4.647	260	297	2.413	125	135	0.289	350	370	0.672
6285.	4.685	180	228	4.285	265	297	2.087	122	145	1.350	350	370	0.672
6315.	4.685	185	235	4.464	270	310	2.608	120	145	1.736	360	370	0.241
6345.	4.685	185	235	4.464	272	310	2.478	120	150	2.083	10	30	0.482
6375.	4.685	193	239	4.107	272	310	2.478	120	150	2.330	20	40	0.719
6560.	11.698	215	245	2.020	300	330	1.425	...	...	...	35	60	1.188
6592.	11.698	215	245	2.020	297	330	2.292	...	...	...	40	55	0.539
6900.	17.861	5	35	2.208	90	125	2.054	193	225	1.878	...	...	...

Table 4. (continued)

Mid-time	Pole	Spot 1			Spot 2			Spot 3			Spot 4		
	area	l_1	l_2	area	l_1	l_2	area	l_1	l_2	area	l_1	l_2	area
HJD244+	(%)	(°)		(%)	(°)		(%)	(°)		(%)	(°)		(%)
6930.	17.861	5	35	2.208	90	130	2.348	193	225	1.878	...	...	...
7080.	17.861	50	80	2.020	130	150	0.950	223	250	1.405	...	...	...
7110.	16.543	50	80	2.020	130	150	0.950	223	250	1.585	...	...	...
7265.	11.698	50	82	2.485	140	180	2.944	248	288	3.187	...	...	...
7295.	11.698	50	82	2.485	140	180	2.944	248	288	3.187	...	...	...
7325.	11.698	60	92	2.485	145	185	2.778	248	290	3.346	...	...	...
7415.	15.267	62	92	1.892	167	197	1.892	253	303	2.601	...	...	...
7440.	15.267	70	100	1.892	167	197	1.892	253	303	3.260	...	...	...
7470.	15.900	80	112	1.737	183	213	1.425	260	315	2.985	...	...	...
7490.	15.900	82	116	1.921	183	213	1.425	260	315	2.985	...	...	...
7610.	17.861	83	108	1.188	183	213	1.288	265	315	2.601	10	20	0.241
7635.	17.861	83	108	1.188	183	213	1.148	265	315	2.601	...	...	...
7665.	15.900	155	190	1.663	250	290	2.522	350	370	0.940	...	...	...
7695.	14.033	152	190	2.230	250	290	2.522	345	360	0.539	...	...	...
7783.	9.042	220	258	3.321	310	343	2.946	23	43	0.904	148	172	1.409
7810.	9.042	220	258	3.392	310	345	3.125	25	43	0.814	148	172	1.409
7838.	9.042	222	262	3.717	310	343	2.629	25	43	0.814	148	172	1.409
8000.	11.143	230	267	2.413	303	333	2.449	40	65	1.188	...	...	...
8030.	11.143	230	267	2.413	303	333	2.449	40	65	1.188	...	...	...
8055.	11.143	230	267	2.413	305	333	2.231	40	67	1.585	...	...	...
8180.	11.143	275	308	2.152	340	364	1.960	83	103	0.950	...	...	...
8210.	11.143	272	309	2.413	335	365	2.449	83	103	1.085	...	...	...
8320.	11.698	261	294	2.563	342	397	4.382	175	195	0.950	...	...	...
8355.	11.698	263	296	2.563	342	390	3.824	200	220	0.950	...	...	...
8385.	11.698	265	298	2.563	343	393	3.983	200	220	0.950	...	...	...
8415.	11.698	270	310	3.107	0	45	3.404	190	210	1.041	...	...	...
8440.	11.698	282	322	3.107	10	55	3.404	200	220	0.950	...	...	...
8705.	13.432	287	327	3.187	105	125	1.085	...	...	...	...	...	...
8725.	13.432	285	325	3.187	105	125	1.085	...	...	...	...	...	...
8755.	13.432	290	335	3.404	105	125	1.130	...	...	...	...	...	...
8800.	13.432	310	355	3.404	105	125	1.130	...	...	...	...	...	...
8895.	13.432	332	395	3.698	140	157	0.730	...	...	...	...	...	...
8925.	13.432	310	340	1.761	145	162	0.651	15	45	1.956	...	...	...
8955.	13.432	298	328	1.761	155	170	0.362	2	40	3.027	...	...	...

it is masked out by short-term variations. In an earlier paper Hall & Busby (1990) computed upper limits of spot lifetimes based on the idea that large starspots will be disrupted by the shear of differential rotation. Figure 5 plots their predicted disruption time scales for three values of the differential rotation coefficient $k = \Delta P/P = 0.02$, 0.05, and 0.10 (note that the corresponding solar value is around 0.2). If we assume that the mechanical shear by differential rotation sets the upper limit to a spot's lifetime, the observed maximum lifetime in turn sets an upper limit to the differential-rotation coefficient, namely approximately 0.04±0.01 according to Fig. 5. This would be differential rotation just 5 to 8 times less than the solar value and one of the strongest among active binaries.

From the observed range of rotation periods of the spots of HR 7275 (Table 5) we obtain $k = 0.022 \pm 0.004$ if we assume that the spots sample the entire 90° range in latitude. This value becomes larger if the spots occur within a more limited latitude range. Furthermore, plotting $\Delta P/P$ versus rotation period for a large sample of late-type stars, Hall (1991) found a relation between stellar rotation and the differential-rotation coefficient k in the sense the faster the rotation the smaller k. Applying this relation to HR 7275 predicts $k \approx 0.08^{+0.07}_{-0.05}$; taking into account a Roche-lobe filling factor of 0.5 for HR 7275. This coefficient is larger than the observed one and also much more uncertain due to the large scatter in the $k - P_{\rm rot}$ relation but is still consistent with the observations and suggests a fairly limited latitude range of spot occurence on HR 7275.

Based on a large number of spots on 26 different spotted stars, including the Sun, Hall & Henry (1993b) obtained a relation between spot radii and lifetime for a given stellar radius. For the K1 giant of the HR 7275 system Fekel et al. (1986) determined a projected equatorial rotational velocity of $v \sin i = 15 \pm 2$ km s^{-1} and, combined with our mean rotation period of 28.3 days and the most probable inclination of the rotation axis

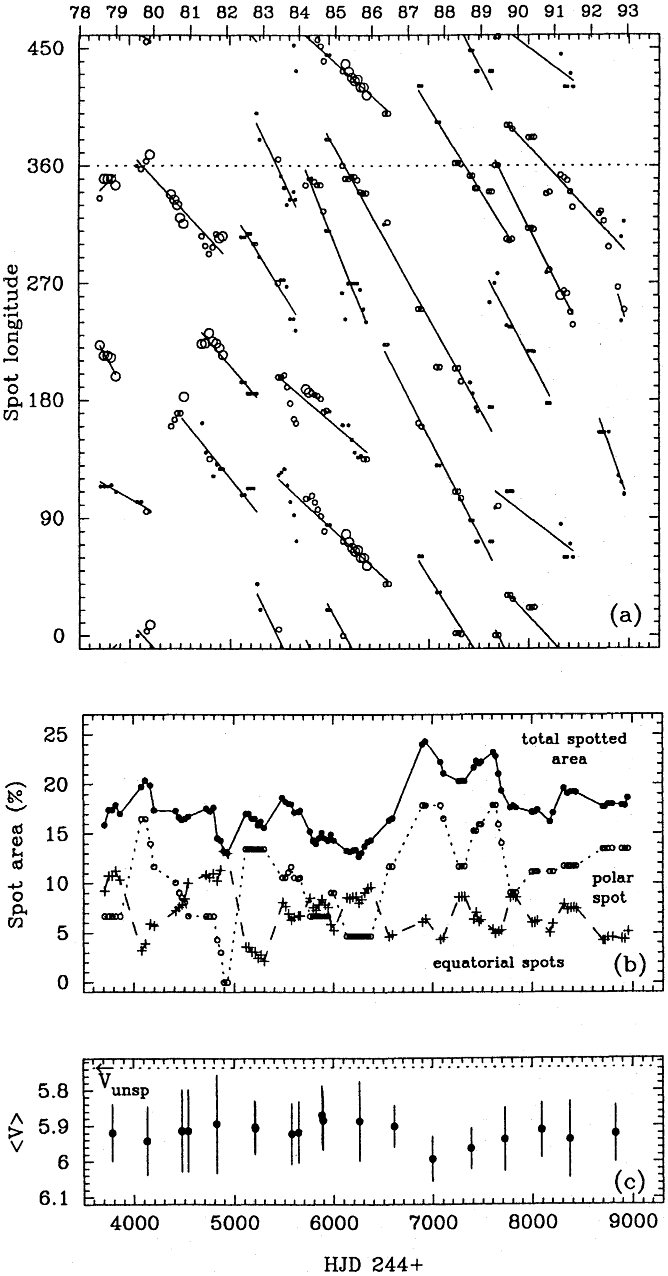

Fig. 4. Spot evolution on HR 7275 from 1978 to 1992. Plotted are the corresponding spot parameters from the fits in Fig. 3. From top to bottom we show the spot longitude (panel a), the spot area in per cent of the total sphere (panel b), and the mean V-light level (dots) from the individual data sets (panel c). The bars in panel (c) indicate the maximum seasonal light-curve amplitude. Panel (b) shows the total spotted area (dots), the area of the polar spot (circles), and the sum of the smaller equatorial spots (plusses). The different symbol size in panel (a) represents different spot area, namely: small circles (0 - 2%), medium circles (2 - 4 %), large circles (4 - 7 %). The lines are linear least-squares fits and are used to determine the rotation periods listed in Table 5

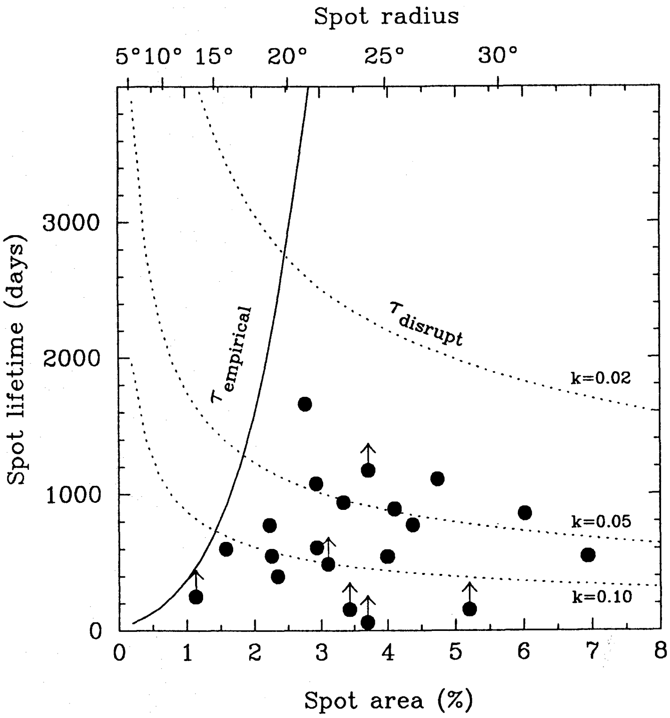

Fig. 5. Spot lifetime versus spot area for the 20 individual spots identified on HR 7275. The dotted lines are the predicted disruption times $\tau_{\rm disrupt}$ as a function of the differential rotation coefficient k and the full line is the empirical relation of the observed (mean) spot lifetimes from a sample of 26 spotted stars taken from Hall & Henry (1993b). The dots are the observations as described in the text, those with arrows denote lower limits.

of 70°, the radius of HR 7275 is 9.0±1.3 $R_\odot$. Equations (6) and (7) of Hall & Henry (1993b) applied to HR 7275 then take the form

$$\tau_{\rm empirical} = 10^{0.13 r_{\rm spot} - 1.48} \quad (2)$$

$$\tau_{\rm disrupt} = P_{\rm rot}/\,k\; 0.285\, r_{\rm spot} \quad \text{if } r_{\rm spot} < 20° \quad (3)$$

$$P_{\rm rot}/\,k\;(0.255 r_{\rm spot} + 0.06) \quad \text{if } r_{\rm spot} > 20° \quad (4)$$

where k is again the dimensionless differential-rotation coefficient, $A_{\rm spot}$ is the area of a spot as a fraction of the whole sphere, and $r_{\rm spot}$ is the spot radius (in degrees) in case the spot is circular and half its longitudinal extension in case the spot is rectangular. In the former case, spot radius and area are related via $\cos r = 1 - 2A$. Note that the empirical $\tau - A$ relation in Eq. (2) is valid only as long as $\tau_{\rm empirical} < \tau_{\rm disrupt}$ and could be interpreted as the stellar analog of the fact that larger *sun*spots have longer lifetimes than smaller sunspots. Bumba (1963) and others already demonstrated that the slow decay of sunspot area is nearly constant in time and equal for a large number of studied cases.

5. Summary and conclusions

We present new broad-band photometry obtained with a fully automatic photoelectric telescope in the years 1987 through

Table 5. Spot rotation periods, lifetimes, and maximum areas

Spot	n	P_{rot} (days)	lifetime τ (days)	max. area (%)
a	5	28.766±0.102	>155	3.43
b	5	28.269±0.069	>155	5.20
c	9	28.492±0.010	>490	3.11
d	16	28.400±0.017	855	6.02
e	18	28.425±0.014	545	4.44
f	13	28.382±0.016	545	6.94
g	14	28.308±0.025	550	2.26
h	9	28.228±0.046	400	2.35
i	24	28.443±0.017	890	4.11
j	27	28.430±0.013	1107	4.74
k	18	28.154±0.037	610	2.94
l	26	28.277±0.009	1660	2.78
m	15	28.252±0.014	1075	2.94
n	16	28.309±0.013	938	3.35
o	11	28.252±0.038	600	1.58
p	12	28.242±0.014	775	4.38
q	20	28.401±0.018	>1172	3.72
r	10	28.456±0.023	775	2.23
s	7	28.125±0.063	>250	1.13
t	3	27.944±0.772	>60	3.70

1992. These data were supplemented with previously published and unpublished V-band photometry from 1978 on – resulting in a total baseline in time of 15 consecutive years – and were used for a detailed spot modeling analysis. Figure 4 shows the results of our time-series approach.

Even though we have fifteen consecutive years of photometry of a star with a fairly long rotational period (28 days), and thus good phase coverage, there seems to be no clear indication of any periodicity, or homogeneous long-term trend, in the spot behavior. This result in itself is very interesting because it might be an indication that in overactive binary stars like HR 7275 the underlying dynamo is quite different to what we believe is the solar dynamo. However, our modeling technique is far from perfect and we again emphasize that we are modeling just the *asymmetric* part of the surface spot distribution while we *assumed* the symmetric part to be in form of a polar spot. One must keep this in mind when interpreting our results. Fig. 1 and Fig. 4c clearly show non-periodic changes of the visual brightness. So far, the faintest light-curve maximum occured in 1987 and the brightest in 1981 with a difference of the peak magnitudes of 0.2 mag in V. This large a variation can not be accounted for with the same spots that produce the rotational modulation and needs to invoke some other feature, e.g. a polar spot always in view or a symmetric spottedness all over the star or a changing average photospheric temperature due to facular contribution that would make the "unspotted" magnitude a function of time. Or, even worse, a combination of all of this.

Spot cycles in evolved RS CVn-type photospheres are obviously not as straightforward to observe as emission-line cycles in main-sequence stellar chromospheres, as for example in 61 Cygni (K5V; P_{rot} = 36 days) with its solar-like sawtooth cycle of 7 years (Larson et al. 1993) or in many other dwarf stars observed in the Mt. Wilson Ca II H & K project. This has primarily three reasons: first, the spot cycle period in evolved stars might be much longer than the time span of the observations (15 to 20 years is the best coverage with photoelectric photometry), second, there are large, superimposed, short-term light variations likely unrelated to a magnetic cycle and most likely due to the birth and decay of individual spots and, third, the light amplitude due to rotational modulation can be as large as the cycle amplitude or even larger. Although not a giant star, BY Draconis is a good example: Phillips & Hartmann (1978) used the Harvard archival plate collection to deduce a spot cycle period of about 50 years, while Rodonó & Cutispoto (1992) found evidence of a fluctuation with relative light minima separated by about 8 years. The observations become even more complicated to interpret if we take into account the stellar analog of a solar Maunder minimum, as suggested by Hartmann et al. (1979) for the RS CVn binary II Peg.

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References

Al-Naimiy H. M., 1978, Ap&SS 53, 181
Applegate J. H., 1992, ApJ 385, 621
Bell R. A., Gustafsson B., 1989, MNRAS 236, 653
Bidelman W. P., 1964, ApJ 139, 405
Bopp B. W., 1984, ApJS 54, 387
Bopp B. W., Dempsey R. C., Pierce G., 1989, IBVS 3351
Boyd L. J., Genet R. M., Hall D. S., Busby M. R., Henry G. W., 1990, IAPPP Comm. 42, 44
Breger M., 1985, PASP 97, 85
Breger M., 1988, PASP 100, 751
Bumba V., 1963, Bull. Astron. Inst. Czech. 14, 91
Dorren J. D., Guinan E. F., 1990, ApJ 252, 296
Eaton J. A., 1992, in Surface Inhomogeneities on Late-Type Stars, eds. P. B. Byrne & D. J. Mullan, Springer, Berlin-Heidelberg-New York, p. 15
Eaton J. A., Hall D. S., 1979, ApJ 227, 907
Eker Z., 1989, MNRAS 238, 675
Fekel F. C., Moffett T. J., Henry G. W., 1986, ApJS 60, 551
Fried R. E., Eaton J. A., Hall D. S., et al., 1982, Ap&SS 83, 181
Guinan E. F., Gimenez A., 1993, in The Realm of Interacting Binary Stars, eds. J. Sahade et al., Kluwer, Dordrecht, p. 51
Hall D. S., 1972, PASP 84, 323
Hall D. S., 1991, in IAU Colloq. 130, The Sun and Cool Stars: activity, magnetism, dynamos, eds. I. Tuominen, D. Moss, & G. Rüdiger, Springer, Berlin-Heidelberg-New York, p. 353
Hall D. S., Busby M. R., 1990, in NATO ASI, Active Close BInaries, ed. C. Ibanoglu, Kluwer, Dordrecht, p. 377
Hall D. S., Henry G. W., 1993a, in IAU Colloq. 136, Stellar Photometry, eds. C. J. Butler & I. Elliott, Cambridge Univ. Press, p. 205

Hall D. S., Henry G. W., 1993b, in Kilkenny Workshop, Robotic Telescopes, eds. B. P. Hine & M. F. Bode, in press
Hartmann L., Londono C., Phillips M. J., 1979, ApJ 229, 183
Herbst W., 1973, A&A 26, 137
Joy A. H., Wilson R. E., 1949, ApJ 109, 231
Larson A. M., Irwin A. W., Yang S. L. S., et al., 1993, PASP 105, 332
Nations H. L., Seeds M. A., 1986, PASP 98, 1105
Nicolet B., 1978, A&AS 34, 1
Phillips M. J., Hartmann L., 1978, ApJ 224, 182
Poe C. H., Eaton J. A., 1985, ApJ 289, 644
Reglero V., Giménez A., deCastro E., Fernandez-Figuero M. J., 1987, A&AS 71, 421
Rodonó M., Cutispoto G., 1992, A&AS 95, 55
Rodonó M., Cutispoto G., Pazzani V., et al., 1986, A&A 165, 135
Scharlemann E. T., 1982, ApJ 253, 298
Seeds M. A., Nations H. L., 1986, IAPPP Comm. 25, 50
Strassmeier K. G., 1992, in Robotic Telescopes for the 1990's, ed. A. Fillipenko, PASPC 34, p. 39
Strassmeier K. G., Bopp B. W., 1992, A&A 259, 183
Strassmeier K. G., Hall D. S., Boyd L. J., Genet R. M., 1989, ApJS 69, 141
Strassmeier K. G., Rice J. B., Wehlau W. H., et al., 1991, A&A 247, 130
Vogt S. S., 1988, in IAU Symp. 132, The Impact of Very High S/N Spectroscopy on Stellar Physics, eds. G. Cayrel de Strobel & M. Spite, Kluwer, Dordrecht, p.253
Young A., Koniges A., 1977, ApJ 211, 836
Young R. K., 1944, JRASC 38, 366
Zeilik M., Elston R., Smith P., Hall D. S., 1984, in Cool Stars, Stellar Systems, and the Sun, eds. S. L. Baliunas & L. Hartmann, Springer, Berlin-Heidelberg-New York, p. 264

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