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$UBV(RI)_C$ and $uvby$ photometry of HD 81410 and starspot distribution in RS CVn objects*

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Abstract. We present $UBVRI$ and $uvby$ photometry of HD 81410 obtained on a total of 40 nights during 1987–90, and an analysis of its long-term photometric behaviour. The star is found to show two well-separated minima in its light curve most of the time; probably there are two preferred effective longitudes about which spots are mainly formed. The migration of the phase of the light minimum usually seen in RS CVn stars is absent in HD 81410.

The rather small spread in the maximum V amplitudes observed in active RS CVn objects seen at different inclinations of rotational axis implies that the longitudinal asymmetry in the distribution of spots, which causes the light modulation, is largely restricted to within around $\pm 40°$latitudes. The total ranges of rotational periods which are quoted in the literature for several spotted stars based on long-term photometry also imply a similar latitudinal extent of spots about the equator. We find that the light and colour curves produced by an equatorial band of spots limited by latitudes and covering the full range of longitudes across the hemisphere visible at light minimum can be approximated reasonably well by two well-separated circular spots. Further, we find that the net effect in the colours produced by limb-darkening depends on the exact distribution of spots on the stellar surface; it could be even negligible for certain spot distributions.

From the spot modeling of the light and colour curves of HD 81410 we find that the maximum temperature difference between the photosphere and spots is around 1400 K. We also find that the light modulation is caused by several small individual spots, and during the epochs of shallow minimum spots are spread out, both latitudinally and longitudinally, over a wider region, as indicated by a higher temperature for the equivalent circular spots at those epochs. It seems that in RS CVn stars the spots occur largely distributed about the equator as in the case of the Sun and the solutions which indicate polar spots result from limiting the number of spots in the modeling to a few.

Key words: starspots – stars: late-type – stars: individual: HD 81410 – stars: individual: IL Hya – binaries: spectroscopic – stars: activity

1. Introduction

The suspected light variability of HD 81410 (=IL Hya) by Cousins & Stoy (1963) was confirmed by Eggen (1973) who observed the star in 1971 and 1972, and found it to be a variable with an amplitude of about 0.5 mag in V. The light curves obtained during the two observing seasons differed appreciably, and a period of 25.4 days was found to satisfy the observations of each seasons separately. Bidelman & MacConnell (1973) listed HD 81410 as a star with K1III spectrum displaying strong $Ca\ II\ \ H$ & K emissions and *filled Balmer lines*. The radial velocity measurements made independently by Wayman and Jones (Eggen 1973) showed HD 81410 to be a single-lined spectroscopic binary.

Raveendran et al. (1982), who observed HD 81410 almost a decade after Eggen (1973), found that the photometric period is in fact close to 12.87 days. They found that the amplitudes of light variation in both B and V had changed drastically during the intervening period, and were only around 0.15 mag. From the observed $(U-B)$ and $(B-V)$ colours of HD 81410 at its light maximum, they suggested that the secondary component of HD 81410 is probably an F dwarf. Fekel et al. (1986) found HD 81410 to show very strong $Ca\ II\ \ H$ & K emission features typical of a late type chromospheric active star, and no evidence for a uv continuum from an F type companion, as suggested by Raveendran et al. (1982). Cutispoto (1993) assigned the spectral types K2-3IV and G4V to the components from the observed colours of HD 81410. The secondary component was detected and its radial velocity measured by Donati et al. (1997) on two high resolution, high S/N spectra taken in December 1993. Recently, Weber & Strassmeier (1998) have reported 12 radial velocities for the secondary component and derived its amplitude; they suggest a spectral type of mid to late F main sequence or G0V-IV for it.

The $Li\ I$ 6708 Å absorption line is very strong in the spectrum of HD 81410. The equivalent width of the line, which does

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* Based on the observations collected at the European Southern Observatory, La Silla

Table 1. $UBVRI$ and $uvby$ magnitudes of the comparison stars of HD 81410

Band	HD 81904	HD 80991
U	9.695±0.008	10.368±0.007
B	8.995±0.005	9.550±0.004
V	8.020±0.004	8.510±0.005
R	7.515±0.006	7.980±0.006
I	7.045±0.004	7.448±0.004
u	10.934±0.007	11.618±0.008
v	9.573±0.006	10.175±0.006
b	8.614±0.005	9.122±0.006
y	8.019±0.005	8.505±0.005

not vary significantly with the photospheric spot visibility, indicates a rather high value of log n(Li) = 1.34, and such a high value is most likely due to a real decrease in Li depletion in HD 81410 (Pallavicini et al. 1992, 1993)

Slee et al. (1984) detected HD 81410 as a highly variable radio source; during the initial phases of the major flare observed on 2 August 1983, the flux density at 5 GHz increased from about 15 to 28 mJy in 1.5 hours, almost by a factor of 2. HD 81410 has strong EUV emission; it is one of the 383 objects contained in the Bright Sources Catalogue compiled from the results of the recent ROSAT-WFC all sky survey in the 60–200 eV energy band (Pounds et al. 1993).

In this paper we present new photometry of HD 81410, and discuss its long-term photometric behaviour. We also discuss the implications of the results of photometric observations of active RS CVn stars on their surface distribution of starspots. Further, we model a set of light and colour curves of HD 81410 obtained at closely spaced epochs to investigate the short-term evolution of spots.

2. Photometry

HD 81410 was observed on a total of 40 nights – in $UBV(RI)_C$ during April 1987 and May 1988, and in $uvby$ during June 1988 and January 1990 – at the European Southern Observatory (ESO), La Silla, Chile, using the 50 cm ESO Cassegrain telescope. HD 81904 and HD 80991 were observed as the comparison stars through out, and all the observations were made differentially with respect to the former. The probable errors in the differential $BVRI$ magnitudes are typically around 0.005 mag, while those in U and $uvby$ are slightly higher. The average $UBVRI$ and $uvby$ magnitudes of the comparison stars obtained from the observations of several runs are given in Table 1, and the differential measurements of HD 81410 were converted to $UBVRI$ and $uvby$ magnitudes using the corresponding values of HD 81904.

The Julian days of observation were converted into photometric phases using the following ephemeris:

$$JD(Hel.) = 2449400.260 + 12^d.90513E,$$

Table 2. Photometric characteristics of HD 81410

Epoch	Amplitude	$V_{\max}$	$V_{\min}$	$\phi_{\min}$	References
1971.17	0.430	7.520	7.950	0.02	Eggen (1973)
1972.20	0.440	7.450	7.890	0.91	Eggen (1973)
1978.98	0.270	7.430	7.700	0.87	Lloyd Evans & Koen (1987)
1980.05	0.145	7.460	7.630	0.61	Lloyd Evans & Koen (1987)
1981.10	0.145	7.470	7.615	0.46	Raveendran et al.
				0.85	(1982)
1982.00	0.090	7.510	7.600	0.81	Lloyd Evans & Koen (1987)
1985.04	0.153	7.410	7.563	0.46	Manfroid et al. (1991)
1987.29	0.105	7.300	7.405	0.96	Present study
				0.46	
1987.93	0.125	7.285	7.410	0.60	Pallavicini et al. (1993)
				0.90	
1988.01	0.130	7.280	7.410	0.63	Sterken et al. (1993)
				0.90	
1988.23	0.117	7.288	7.405	0.63	Sterken et al. (1993)
1988.41	0.145	7.260	7.405	0.61	Present study
1988.89	0.091	7.283	7.374	0.57	Sterken et al. (1993)
				0.97	
1989.12	0.060	7.300	7.360	0.47	Cutispoto (1993)
				0.87	
1989.20	0.046	7.294	7.340	0.31	Sterken et al. (1993)
				0.86	
1989.96	0.20	7.24	7.44	0.11	Cutispoto (1995)
1990.00	0.195	7.230	7.425	0.10	Sterken et al. (1993);
					Present study
1990.46				0.10	Sterken et al. (1993)
1990.95	0.156	7.314	7.470	0.00	Manfroid et al. (1995)
				0.54	
1992.09	0.148	7.287	7.435	0.86	Manfroid et al. (1995)
1993.00	0.150	7.250	7.400	0.56	Sterken et al. (1995)
1994.12	0.120	7.305	7.425	0.34	Sterken et al. (1995)
1995.09	0.17	7.28	7.45	0.10	Strassmeier et al. (1997)
1996.11	0.25	7.23	7.48	0.82	Strassmeier et al. (1997)

where the initial epoch corresponds to the conjunction with the primary in front calculated from its time of maximum radial velocity and the period is the orbital period (Weber & Strassmeier 1998). The V and y magnitudes, and the various colours obtained by us are plotted in Figs. 1a,d,h; the observations obtained by Sterken et al. (1993) close to the period of our observations are also plotted in Fig. 1h.

3. Photometric characteristics

The photometric parameters, the brightness at light maximum and minimum, $V_{\max}$ and $V_{\min}$, the phase of light minimum $\phi_{\min}$, and the amplitude of light variation estimated from the present data and those available in the literature are given in Table 2.

The shape of the light curve of HD 81410 is found to change even within a few orbital cycles. The observations (see Table 2 for the references) of HD 81410 during the closely spaced epochs 1988.01, 1988.23, 1988.41, 1988.89, 1989.12 and 1989.20, which are plotted in Figs. 1b–g, clearly bring out the large-scale, short-term variability that occurs in its light curve. During this period the light curve changed from being

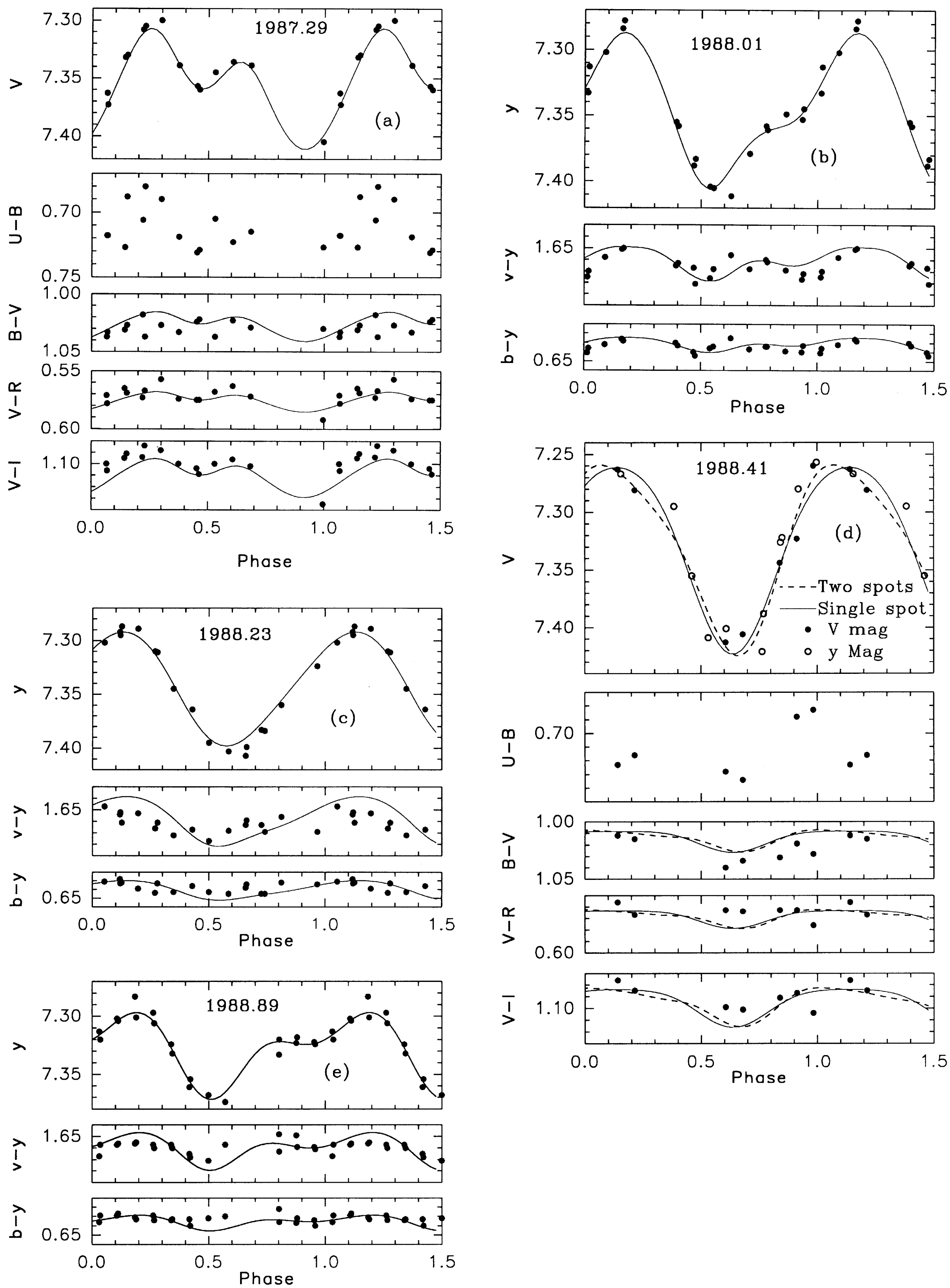

Fig. 1a–h. Light and colour curves of HD 81410; the mean epochs of observation are indicated (see Table 2 for the references). The smooth continuous curves represent the results of spot modeling

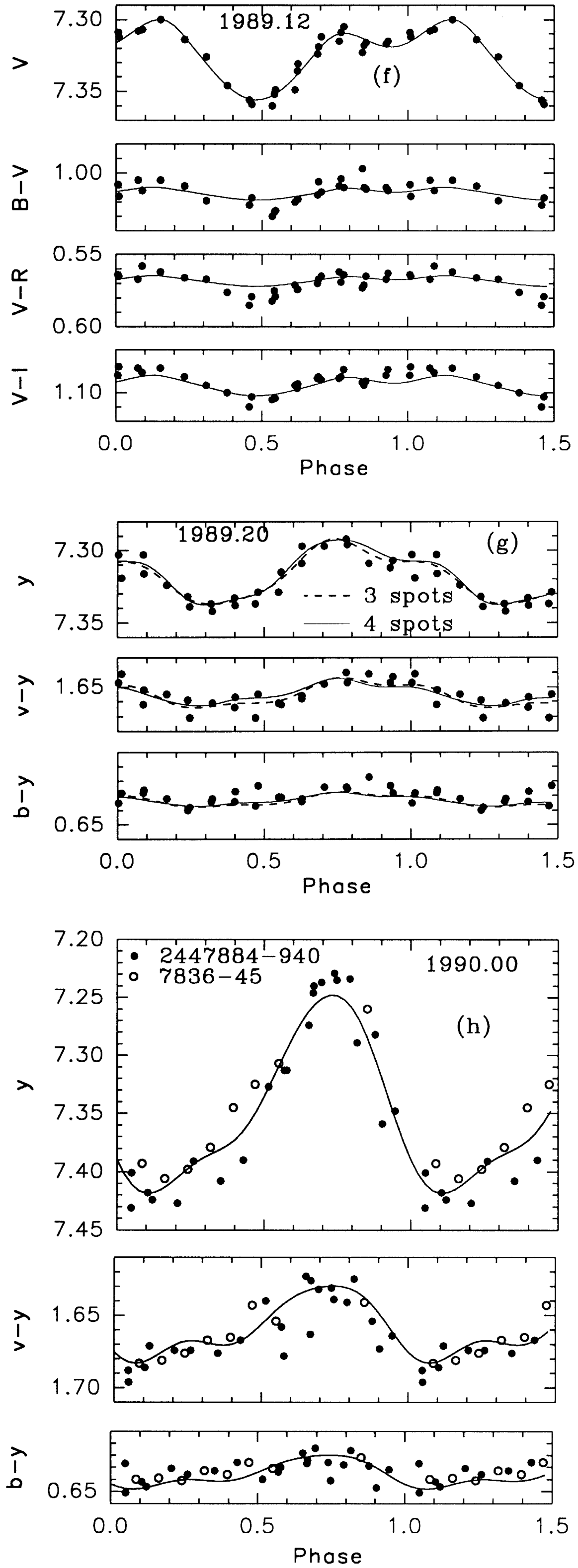

Fig. 1a–h. (continued)

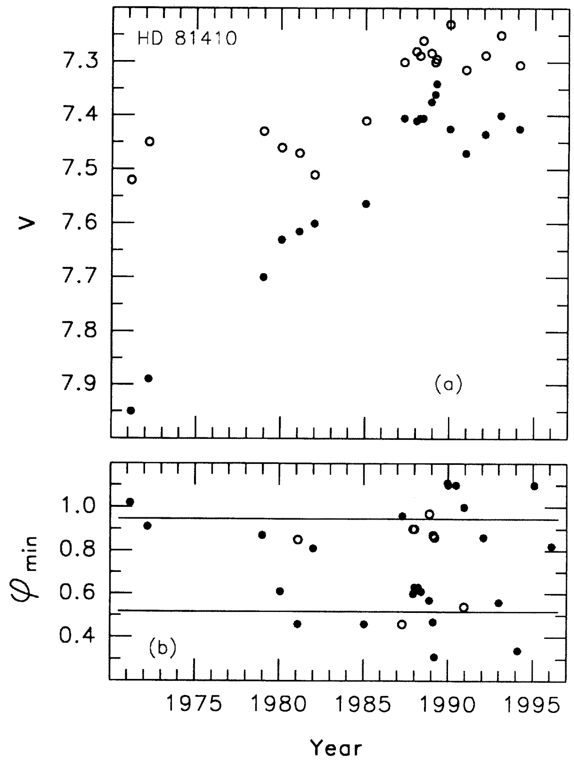

Fig. 2. **a** Plots of $V_{\rm max}$ (*open circles*) and $V_{\rm min}$ (*filled circles*) of HD 81410 against the mean epoch of observation. **b** Plot of phase of light minimum against the mean epoch. Open circles denote the secondary minima

of double minima to a single minimum and again back to double minima. It is interesting to see that all the while the deeper minimum remained more or less at the same phase, between $0.^p5$ and $0.^p6$.

The variations in $U-B$, $B-V$, $V-R$ and $V-I$ shown by HD 81410 are in phase with the V light curve in the sense that the colours tend to be redder at the light minimum. The amplitude of variation is the largest in $V-I$ colour. The colours $u-y$, $v-y$, and $b-y$ also show variations over the photometric phase in the same sense as the broadband colours with the $v-y$ colour showing the largest amplitude.

Fig. 2a is a plot of $V_{\rm max}$ and $V_{\rm min}$, the brightness at light maximum and minimum, against the corresponding mean epoch of observations. The largest amplitude of light variation so far observed occurred during 1971 and 1972 (0.45 mag), and the smallest during March 1989 (0.05 mag). Both $V_{\rm max}$ and $V_{\rm min}$ show a large range in magnitudes. The unspotted brightness, which is an important parameter in quantitative spot modeling, can be determined if photometry spanning over a large time interval is available. As seen from Table 2 HD 81410 has been observed photometrically almost every year starting from 1978 till 1996. The maximum $V_{\rm max} = 7.23$ mag observed during 1990 probably corresponds to the unspotted photospheric magnitude. An inspection of Fig. 2a (see also Fig. 11 of Strassmeier et al. 1997) shows that during the period 1971–1985 the $V_{\rm max}$ remained more or less constant around 0.20 mag below the maximum, whereas the $V_{\rm min}$ monotonically became brighter from 1971 till 1987. The increase in $V_{\rm min}$ during this interval was more than 0.5 mag. After 1987 both $V_{\rm max}$ and $V_{\rm min}$ did not change appreciably, even though there were small fluctuations in their values.

The total range in brightness shown by HD 81410, in the sense $V_{\rm max}$ (brightest) $minus$ $V_{\rm min}$ (faintest), is around 0.70 mag. This is comparable to that observed in active RS CVn systems like II Peg and DM UMa (Mohin & Raveendran 1993, 1994), and therefore, the $V_{\rm min}$ observed in 1971 by Eggen (1973) is probably close to its saturation value.

From 1971 to around 1985 the $V_{\rm max}$ of HD 81410 was about 0.20 mag below the maximum brightness so far observed, indicating that the starspots never disappeared from the field of view. A drastic change which resulted in a substantial reduction in the overall spot activity seems to have happened sometime after 1982 because both $V_{\rm max}$ and $V_{\rm min}$ became brighter by almost 0.20 mag.

Table 2 shows that the light curves of HD 81410 display two minima quite often, implying a highly asymmetrical surface brightness distribution most of the time. The observations obtained so far do not show any flat-topped light curve with $V_{\rm max}$ close to its maximum observed value, indicating that the spots responsible for the light modulation always had large longitudinal extents. The $\phi_{\rm min}$ determined from such light curves would give the effective longitude of the spot or spot group. Similarly, from the large light amplitudes observed it is reasonable to expect a large latitudinal extent also for the spots. Fig. 2b is a plot of the phase of light minimum against the corresponding mean epoch of observations. There is an indication of two preferred effective longitudes about which spots are generally formed, one around $0^p.50$ and the other around $0^p.95$. The scatter about these values seen in the figure partly arises from the errors in the estimation of $\phi_{\rm min}$ because of the large intrinsic scatter in the light curves as a result of folding the observations over several photometric cycles and the large longitudinal extent of the light minimum. Probably, several spots are involved in producing the observed light modulation, and the small short-term fluctuations in the effective longitudes, which might also be occurring, is caused by the rather short life-times (a couple of rotational cycles) of individual spots. The migration of $\phi_{\rm min}$, arising from a difference in the orbital and photometric periods, that are usually observed in RS CVn systems, is not very prominent in the case of HD 81410, which implies that the effective latitude of the spot or spot groups responsible for the light modulation is in synchronous rotation with the orbit.

In Fig. 3 we have plotted the brightness at light maximum and minimum, $V_{\rm max}$ and $V_{\rm min}$, given in Table 2 against the corresponding amplitudes. There is an indication that at amplitudes larger than 0.2 mag an increase in amplitude occurs more as a result of a decrease in the brightness at light minimum; at amplitudes smaller than this apparently there is no such correlation. From the figure it is seen that at low amplitudes (< 0.1 mag) both the brightness at light maximum and minimum converge to the same value. Therefore a smaller amplitude, mostly likely, arises not from a reduction in the spot activity, but rather from a more uniform distribution of spots across the longitude.

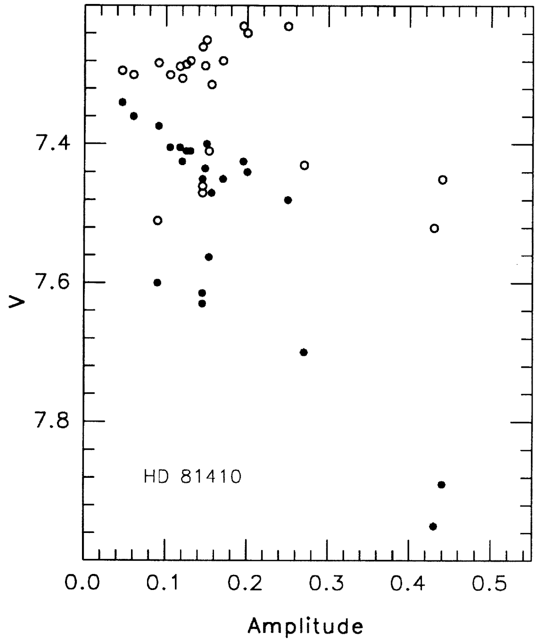

Fig. 3. Plots of $V_{\rm max}$ (*open circles*) and $V_{\rm min}$ (*filled circles*) against the corresponding amplitude of light variation

4. Starspots in RS CVn stars

Almost all RS CVn systems, for that matter all rotating variables, usually exhibit continuously varying light over the photometric cycle; flat-topped light curves are seldom observed. Even in the case of eclipsing RS CVn variables, with the inclinations of the rotational axis $i \sim 90°$, the outside eclipse variation arising from the spotted nature of the active star is nearly sinusoidal. This implies that the spots which modulate the observed flux have a large longitudinal spread $\sim 180°$.

4.1. Latitudinal extent

Both the light curve modeling using large, discrete spots, and the Doppler imaging using weak photospheric lines suggest the presence of long-lived polar spots, which have no solar analogue, in active stars. However, recently, Unruh and Collier Cameron (1997) have found differences in the Doppler images obtained from the sodium, and calcium and iron line profiles – the images obtained from sodium D lines indicate less high latitude structure and give more reliable light curve predictions than the images derived from several weaker photospheric lines.

For an inclination of the rotational axis i the main contribution to the rotational modulation comes from spots present in the $\pm i°$ latitudinal belt and the maximum possible amplitude increases drastically with the inclination. For example, for a spot–photosphere temperature difference of 1000 K an increase in i from 40° to 60° increases the maximum possible amplitude from 0.5 to 1.2 mag, a range of about 0.7 mag. For a tem-

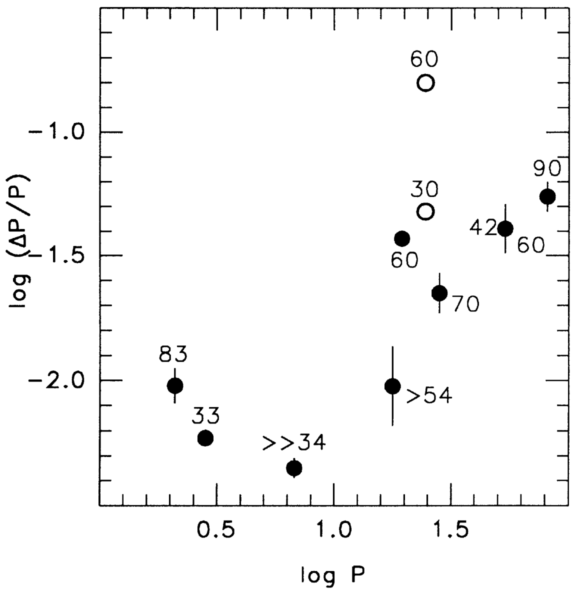

Fig. 4. Plot of log $(\Delta P/P)$ of the well-observed spotted stars against their respective $logP$. The corresponding positions for the Sun are indicated as open circles. The orbital inclinations of the binaries are also indicated in the figure.

perature difference of 1500 K the range would be more than 1 mag. However, the spread in the maximum observed amplitudes for the four active, well-observed, single-lined systems – DM UMa (0.32 mag, Mohin & Raveendran 1994), II Peg (0.50 mag, Mohin & Raveendran 1993), HD 12545 (0.60 mag, Nolthenius 1991), and HD 81410 (Table 2) – is only around 0.25 mag. If spots are confined to $\pm 40°$ latitude the increase in amplitude when seen at $i = 60°$ instead of $i = 40°$ is about 0.2 mag. The corresponding increase is around 0.3 mag if the spots are cooler than the photosphere by 1500 K. Hence it is tempting to conclude that the longitudinal asymmetry in the distribution of spots, which causes the observed light modulation, is largely restricted to around $\pm 40°$ in latitude. Such a conclusion, of course, depends on the following assumptions: (i) the inclinations of the above four active stars are different and they show at least a spread of about 20°; it is highly unlikely that all of them have the same inclination for the rotational axis, (ii) all these objects show similar levels of spot activity, which is quite possible in view of their similar spectral types, and (iii) spots form on both sides of the stellar equator with equal probability as in the case of the Sun.

Hall (1991) has found that the differential rotation is correlated strongly with the rotation period, in the sense that rapidly rotating stars approach solid body rotation. The existence of such a tight relationship as found by him indicates the possibility that the differential rotation in spotted stars is similar to that of the Sun, with the poles rotating slower than the equator. For a given spotted star with solar type differential rotation the photometric period would depend on the effective latitude of the spots or spot groups that produces the light modulation. The total range of photometric periods ($\Delta P = P_{\rm max} - P_{\rm min}$) derived from long-term photometry will be a rough measure of the total latitudinal extent of spots on its surface since the higher the latitude of spot occurrence, the larger will be the $P_{\rm max}$. In Fig. 4 we have plotted the $log(\Delta P/P)$ against the corresponding $logP$ of nine well-observed objects – λ And, σ Gem, II Peg, V711 Tau, HR 7275, V350 Lac, V478 Lyr, BM Cam and V1149 Ori. The total range of rotational periods ΔP and the average period P of these objects are taken from Henry et al. (1995), Strassmeier et al. (1994), Crews et al. (1995) and Hall et al. (1990, 1991, 1995). The positions of the Sun calculated with the rotational periods at 30°and 60°latitudes taken as the values of $P_{\rm max}$ are also indicated in the figure. It is quite interesting to see that λ And, σ Gem, HR 7275, BM Cam and V1149 Ori lie close to the position of the Sun with log $(\Delta P/P)$ corresponding to 30°latitude, and that corresponding to 60°latitude is well above the mean position occupied by these objects. The effect of the weak correlation (at 2σ significance level) of log $(\Delta P/P)$ on the Roche-Lobe filling factor found by Hall (1991) is expected to be small around the periods of these stars. Again, it is tempting to conclude that in spotted stars, in general, the spots mainly occur within around $\pm 40°$effective latitudes.

If there is no limit on the latitudinal extent for the formation of spots, the observed $\Delta P/P$ should show a dependence on the inclination i in addition to the dependence on P discussed above. All the stars plotted in Fig. 4 have reliable estimation of inclination of rotational axis. The most likely values of i, sources of which are the same as those of the total range of rotational periods, are indicated against the corresponding points in Fig. 4. No dependence of $\Delta P/P$ on i is evident from the figure, indicating that the latitudinal spread of the spots is similar in all the stars considered.

The spot activity, probably, is not always just restricted to within $\pm 40°$latitudes. In the case of DM UMa ($i \sim 40°$, Crampton et al. 1979) the total range in V observed, $i.e.$, $V_{\rm max}$(brightest) – $V_{\rm min}$(faintest), is 0.52 mag (Mohin & Raveendran 1994). Assuming that $V_{\rm max}$(brightest) corresponds to the unspotted magnitude and that spots are cooler than the surrounding photosphere by 1000 K, then such a range requires that even for 100% spot coverage spots should occur well beyond $\pm 40°$ in latitude in the hemisphere visible at light minimum at that epoch.

4.2. Limb-darkening effects

The theoretical light curve modeling available in the literature shows that the effect of wavelength dependence of limb-darkening on the colour variation over the photometric phase could be significantly larger than that of the temperature difference between the spot and photosphere. All the spot models that demonstrate such an effect assume circular spots which cross the centre of the projected stellar disc during the rotation of the variable (Poe & Eaton 1985; Eker 1994). The light and colour curves due to a rectangular spot bounded by the latitudes $\pm 20°$ and extending over the full range in longitude on the hemisphere visible at light minimum are plotted in Fig. 5. The angle between the rotational axis and line of sight was assumed to be 60°, and the spot was assumed to be 1000 K cooler

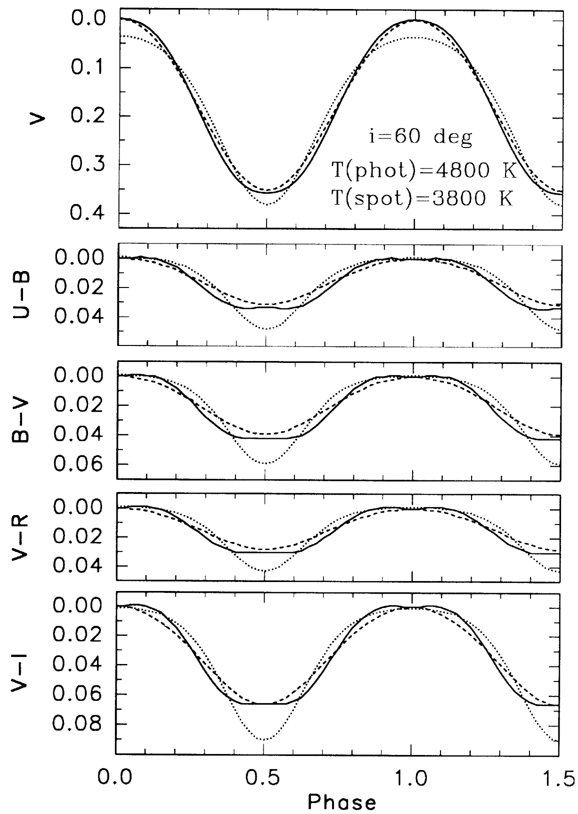

Fig. 5. Light and colour curves due to an equatorial band of spot with linear limb-darkening (LD) and with no LD (*solid lines* and *dashed lines*), and due to an equivalent circular spot with linear LD (*dotted lines*)

than the photosphere. The calculations were done for both (i) no limb-darkening (dashed line) and (ii) linear limb-darkening (solid line). The linear limb-darkening coefficients in $UBVRI$ given in Strassmeier & Olah (1992) and Eker (1994), namely 0.96, 0.88, 0.75, 0.61 and 0.50, respectively, were used in the computations. Both the photospheric and spotted regions were assumed to follow the same limb-darkening law. From Fig. 5 it is clear that the light and colour curves corresponding to the two cases differ only slightly indicating that the colour variations are caused by the temperature effects rather than by the limb-darkening effects. The amplitudes of colour curves in both cases are nearly same. The difference is only in their shapes, with the colour curves with limb-darkening showing nearly flat maxima and minima.

A circular spot of 39° radius at a polar distance of 30° also produces a continuous light curve with an amplitude and shape similar to that of the rectangular spot considered above. Fig. 5 also shows the colour and light curves due to such a circular spot. The limb-darkening was assumed to be linear and the same as those quoted above. It is clear from the figure that the colour curves due a circular spot differs significantly, both in amplitude and shape, from that due to an extended rectangular spot. The former curves are flatter at maximum and show deeper minimum than the latter curves. The amplitudes of all colour curves due to the circular spot are larger than those due to the rectangular spot by more than 50%. We conclude that the net effect in the colours produced by the limb-darkening depends on the exact distribution of spots on the stellar surface; it could be even negligible for certain spot distributions.

Table 3. Circular spot parameters derived for the synthetic light curve due to an equatorial band of spot.

No. of spots	Polar dist. (°)	Longitude (°)	Radius (°)	Frac. area	Temp. (K)	σ of fit (mag)
1	29.1±0.4	180.2±0.5	38.0±0.4	0.10	3702±38	0.0259
2	63.4±0.7	134.9±0.5	26.9±0.1	0.10	3622±5	0.0032
	63.6±0.7	225.5±0.5	26.9±0.1			
3	84.5±0.4	119.0±0.2	25.3±0.1	0.14	3741±5	0.0009
	84.0±0.6	180.2±0.4	26.1±0.2			
	84.5±0.4	241.4±0.2	25.3±0.1			
4	89.9±0.1	110.7±0.1	22.9±0.1	0.16	3799±1	0.0001
	90.1±0.1	156.0±0.3	24.4±0.1			
	90.1±0.1	204.4±0.3	24.4±0.1			
	89.9±0.1	249.1±0.1	22.9±0.1			

4.3. Non-uniqueness of spot modeling

We have used a modified version of the computer program in Fortran developed by Mohin & Raveendran (1992) to solve for the spot parameters from a given light curve. In order to see how accurately the resulting equivalent spots reproduce the light curves being solved, the synthetic curves in $UBVRI$ due to an equatorial band of spot described above and plotted in Fig. 5 were subjected to an analysis. A spot extended longitudinally instead of latitudinally was considered because the continuously varying light over the photometric phase usually observed in an RS CVn star indicates a large longitudinal spread for the spots.

Four different trials, corresponding to the cases of a single, two, three and four spots, were made, and in all cases the convergence of the solutions could be easily obtained. The temperatures of the spots were assumed to be the same for all the spots in the cases where the number of spots assumed were more than one. The final spot parameters for the four cases are given in Table 3. It is clear from the standard deviation of fit (σ) given in Table 3 that the single-spot assumption gives a poor approximation to the light and colour curves while the two-spot assumption gives an acceptable fit to the synthetic data. The light and colour curves corresponding to the three- and four-spot assumptions are found to be mutually indistinguishable and in excellent agreement with the data.

Since the light continuously varies over the photometric cycle, the single-spot solution gives a large radius and a high latitude for the spot; half of the spot lies in the circumpolar region. As the number of spots assumed is increased their sizes become smaller and they shift towards the equator where the spot is assumed to be present while synthesizing the data; when their number becomes four the spots slightly overlap and produce an equatorial band with nearly uniform width. The area occupied by the spots as a fraction of the total area of the stellar surface is also given in Table 3. The fractional area of the equatorial spot is 0.16. Both the single- and two-spot assumptions give the fractional area as 0.10, about 50% smaller, where as the three-spot assumption gives almost the correct value. The spot temperature was assumed to be 3800 K, 1000 K cooler than the photosphere. It is interesting to see from the Table 3 that the total range in the spot temperatures derived is only around 150 K; the four-spot assumption gives the assumed temperature exactly.

The light minimum of the synthetic curve occurs at $0.^p5$, corresponding to a longitude of 180°. However, in the case of the two-spot assumption the spots are separated by 90° in longitude and therefore the real light minimum occurs at their mean longitude. In the present case the spots are of equal size. In an actual case the spots could be of different sizes and the longitude estimated from the light curve would then correspond to a longitude weighted by the intensity distribution on the hemisphere visible at light minimum. Usually, the migration of the light minimum observed in RS CVn Systems is attributed to a migration of spot or spot group as a result of a difference between the actual period and the period used in folding the observations. If there are more than one prominent spot group, then the migration of the phase of the light minimum may not represent a true migration of a spot or spot group because the apparent shift in the phase of the light minimum may be arising from a change in the relative strengths of the various spot groups.

Table 4. Spot parameters derived from the light curves of HD 81410

Mean epoch	Polar distance (°)	Long. (°)	Radius (°)	Temp. (K)	Fract. area	σ of fit (mag)
1987.29	105±6	165±1	24±2	4094±45	0.041	0.005
	17±1	330±1	35±1	4094±45	0.088	
1988.01	39±5	194±2	22±1	3928±117	0.035	0.007
	70±13	322±4	15±1	3928±117	0.017	
1988.23	22±2	188±5	40±4	4375±55	0.114	0.010
	14±1	270±10	40±4	4375±55	0.039	
1988.41[a]	20±1	229±2	28±1	3439±199	0.056	0.017
1988.41[b]	40±4	253±5	20±1	3361±199	0.028	0.016
	15±4	164±8	20±1	3361±199	0.028	
1988.89	42±4	180±2	43±6	4553±45	0.126	0.007
	20±2	338±2	43±6	4553±45	0.102	
1989.12	11±1	173±1	26±1	3509±42	0.050	0.006
	99±6	345±1	13±1	3509±42	0.011	
1989.20[c]	38±5	79±3	33±4	4531±48	0.077	0.006
	32±4	195±3	33±4	4531±48	0.077	
	108±6	326±3	33±4	4531±48	0.077	
1989.20[d]	49±13	58±11	25±4	4460±80	0.047	0.007
	87±17	136±10	25±4	4460±80	0.047	
	85±18	212±7	25±4	4460±80	0.047	
	94±12	315±7	25±4	4460±80	0.047	
1990.00	56±4	20±2	28±3	4219±137	0.055	0.021
	37±2	322±3	137±2	4219±137	0.0055	

[a] Single spot
[b] Two spots
[c] Three spots
[d] Four spots

5. Modeling of the light and colour curves of HD 81410

HD 81410 is a non-eclipsing binary and hence its orbital inclination i is unknown. An uncertainty in i will be directly reflected on the polar distance derived for the spots. Donati et al. (1997) derive a value of $i = 59°\pm4°$, where as Weber & Strassmeier (1998) estimate $i = 56°\pm6°$; we assumed $i = 60°$ in the starspot modeling of the light curves of HD 81410.

The unspotted brightness of the star in each wavelength band observed is an important parameter which has a direct effect on all the spot parameters, $viz.$, polar distance, radius and temperature. The problems associated with the assumption of the unspotted magnitudes have been discussed in detail by Poe & Eaton (1985). The light curves in U and u bands show a large scatter, and therefore only measurements in $BVRI$ and vby bands were subjected to the method of spot modeling described in the previous section. The following values, which are the brightest observed so far in the corresponding bands, are assumed to represent the unspotted magnitudes: B = 8.240, V = 7.230, R = 6.650, I = 6.145, v = 8.860, b = 7.850 and y = 7.230 mags.

The photospheric temperature of HD 81410 was assumed to be 4750 K, consistent with its $(B-V)$ colour index (Donati et al. 1997). Calculations were made with the same linear limb-darkening law for both the spotted and unspotted photospheric regions. Mohin & Raveendran (1992) have shown that the spot parameters derived under such an assumption and the more general assumption that spotted and unspotted regions follow different quadratic limb-darkening laws differ only marginally and are well within the uncertainties involved in their determination. The linear limb-darkening coefficients in $BVRI$ bands were taken as the same as those mentioned earlier in connection with the synthetic light curves. The coefficients in vby bands, 0.91, 0.84 and 0.75, respectively, were derived from an interpolation of the values given by Claret & Gimenez (1990).

In order to study the short-term evolution of spots, we have modeled a sample of closely spaced light curves that showed drastic changes, and the results are given in Table 4. The smooth, continuous curves in Figs. 1a–h represent the computed light and colour curves. The computed curves in all cases closely approximate the observations; the factors which might be contributing to the disagreement (∼ 0.02 mag) include the black-body assumption for the radiation emitted by both the spotted and unspotted regions, and the uncertainty in the unspotted magnitudes in various bands. In general the standard deviations of fit σ are comparable to the scatter in the light curves due to the folding of observations over several rotational cycles. We have seen in an earlier section that the colour curves depend to a large extent on the exact distribution of spots on the stellar surface because of the limb-darkening effects. Therefore, another factor which might be contributing to the disagreement between the computed and observed colour curves is the difference between the actual spot distribution on the star, which may be complex, and the assumed.

The results presented in the previous section show that the spot parameters, polar distance and radius, and sometimes even longitudes derived from the observed light curves could misrepresent the actual situation, even when the light and colour curves computed from these parameters closely reproduce the observations; the only parameter less effected seems to be the spot temperature. This is amply demonstrated in Table 3.

The single- and two-spot solutions give almost similar overall fit to the observations obtained during 1988.41 (Fig. 1d). In the latter solution both the spots were assumed to be of the same radius. Again the spot temperatures in the two cases agree mutually very closely. The light curve obtained during 1989.20 (Fig. 1g) shows the smallest amplitude so far observed. It shows a broad and asymmetric light minimum. There is only a slight indication of a secondary minimum. In this case also two solutions were obtained, $viz.$, with three- and four-spot assumptions. The corresponding σ of fit are 0.006 mag and 0.007 mag. Both sets of computed curves closely match the observations. The temperature obtained in the two cases again agree mutually. In both cases the spots were assumed to be of the same radius.

The observations (mean epoch = 1989.12) of Cutispoto (1993) plotted in Fig. 1f were obtained about a month before the above mentioned observations. The corresponding light curve shows a slightly larger amplitude and a well-defined secondary minimum. The σ of fit is 0.006 mag, similar to those for the solutions obtained for the observations during 1989.20. It is interesting to see that the spot temperature derived from the 1989.20 data is higher by $\sim$1000 K than that derived from the 1989.12 data. We have seen above and also from the solutions of the synthetic data that the derived temperature of the equivalent circular spot(s) is less affected by the assumption on the number of spots. We interpret the higher temperature observed during 1989.20 as follows: The light modulation was caused by several small individual spots or spot groups, and they were more spread out during 1989.20 than during 1989.12, and hence the equivalent circular spots included a larger region of the unspotted photospheric region. Therefore, during epochs of smaller amplitudes for the light variation the spots are more spread out across the stellar surface. During these epochs the brightness at light maximum is invariably well below the unspotted magnitude, implying that spots are spread out both latitudinally and longitudinally. This sort of spot distribution at low light amplitudes is, probably, true for all the active RS CVn stars.

When their number is increased from three to four in the modeling of the 1989.20 data we see that the spots become smaller and shift towards the equator, as in the case of the circular spot solutions of the synthetic data corresponding to an equatorial band of spots given in Table 3. We have seen that as the number of spots is increased, the solutions approach more and more close to the real situation. Therefore, it is quite possible that the spots are distributed about the equator as in the case of the Sun, but with a latitudinal extent significantly larger than $\pm 30°$; the solutions which indicate polar spots may be the result of limiting the number of spots in the modeling to just one, two or three.

6. Conclusions

From an analysis of the long-term photometry of HD 81410 we find that two prominent spot groups, well-separated in effective longitudes, were present on its surface most of the time, as indicated by the presence of two light minima; probably there are two preferred effective longitudes about which spots are usually formed. The migration of the phase of the light minimum usually observed in RS CVn stars is lacking in the case of HD 81410 suggesting that the effective latitude of the spots is in synchronous rotation with the binary orbit.

The light curve of HD 81410 evolves drastically rather fast. During 1988 the light curve changed from being of double minima to single minimum and back to double minima. The deeper minimum, however, remained anchored more or less at the same phase, between $0.^p5$ and $0.^p6$, through out. The colors are found to vary in phase with the light variation in the sense that the star is redder at light minimum. During 1971–85 the brightness at light maximum remained more or less constant around 0.20 mag below the maximum ever observed, where as the brightness at light minimum monotonically increased from 1971 till 1987, by more than 0.5 mag. The largest V amplitude observed is 0.45 mag and the smallest 0.05 mag. The total range in brightness (difference between the brightest $V_{\max}$ and faintest $V_{\min}$) observed is around 0.70 mag, and is similar to that seen in other active RS CVn systems, like, II Peg. There is an indication that at amplitudes larger than 0.20 mag an increase in amplitude results from a decrease in the brightness at light minimum.

We find that for a reasonable level of spot coverage it is essential that in active RS CVn systems, like, DM UMa, II Peg, HD 81410, etc., the spots should extent well-beyond $\pm 40°$ in latitude at least at certain epochs, and the photosphere–spot temperature difference should be more than 1000 K. The spread in the maximum amplitudes in V observed in DM UMa, HD 81410, II Peg and HD 12545 is only around 0.25 mag. If these objects show at least spread of about 20° in the inclination of their rotational axes, assuming similar levels of spot activity in all these stars, it is tempting to conclude that the longitudinal asymmetry in the distribution of spots, which causes the observed light modulation, is largely restricted to within around $\pm 40°$ latitudes in these objects. A strong support for such a possibility comes from a consideration of the total ranges of rotational periods quoted for several spotted stars from long-term photometry in conjunction with the variation of rotational period with latitude in the Sun.

The investigation of synthetic light curves also shows that the effects of limb-darkening in the amplitudes and shapes of colour curves depend on the exact distribution of spots on the stellar surface. It is found that when the spots have a larger extension in longitudes than in latitudes the limb-darkening effects are negligibly small and the colour variations produced are entirely caused by the temperature effects.

A modified version of the spot modeling program developed by Mohin & Raveendran (1992) was applied to synthetic light curves in $UBVRI$ due to an equatorial band of spots covering 180°longitude. The single-spot assumption is found to give a poor approximation to the light and colour curves whereas the two-spot approximation is found to give acceptable fits to the synthetic light and colour curves. Those corresponding to the three- and four-spot assumptions are mutually indistinguishable and excellently reproduce the synthetic data. Interestingly, the spot temperatures derived in all the cases are close to the assumed input value, and show only a spread of about 150 K. The results clearly indicate that if there are more than one prominent spot group the light curve could still show a single well-defined minimum, and hence the migration of the phase of light minimum may not represent a true migration of a spot or spot group because the apparent shift in the phase of the light minimum may be arising from a change in the relative strengths of the various spot groups.

We have modeled a series of eight light curves of HD 81410 which gave the standard deviation of fit comparable to the scatter in the light curve. It is found that the maximum temperature difference between the spots and the photosphere is around 1400 K in HD 81410. The spot temperature derived is comparatively higher (around 4500 K) when the light curve has a shallow minimum. This implies that during such epochs the spots are spread out over a wider region on the stellar surface, both longitudinally and latitudinally, and hence the circular spot approximation for the spot group forces the equivalent spots to include a larger region of the unspotted photospheric region also. As the number of spots is increased in the modeling, it is found that the spots shift closer to the equator indicating that spots are most likely distributed about the equator, and therefore the solutions which indicate polar spots are the result of limiting the number of spots in the modeling to a few.

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