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Spot Activity in the RS CVn Binary HR 1099

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Abstract. *UBV* photometry of HR 1099 obtained during the 1979–80 and 1980–81 observing seasons is presented. An analysis of the available data shows that the brightness at the light curve maximum increases as the wave amplitude increases, while the brightness at the light minimum remains almost the same. In terms of the starspot model it implies that there is always a hemisphere of the active component that is nearly ‘ saturated ’ with spots and that spots occupy a larger fraction of the stellar surface when the wave amplitude is smaller. The continuous migration attributed to the photometric wave by various authors is far from certain. The amplitude of the wave has a sharp rise followed by slow decay with a period around 5–6 yr. It is found that the two-spot model proposed by Dorren and Guinan (1982) is inadequate to describe all the observed photometric peculiarities of HR 1099.

Key words: *UBV* photometry—RS CVn variables—spot activity

1. Introduction

HR 1099 (V711 Tau) is one of the brightest members of the RS Canum Venaticorum type systems and its spectral peculiarities were discovered by Bopp and Fekel (1976). Since its recognition as a strong and variable radio source (Owen, Jones and Gibson 1976), HR 1099 has been the subject of intensive spectroscopic and photometric studies by several investigators. It is a double-lined spectroscopic binary with an orbital period around 2·84 day. Bopp and Fekel (1976) have classified both components as G5 V or slightly later, but the spectral types suggested by Popper (1978) for the components are K1 IV and G5 IV. The most prominent spectral feature of HR 1099 in particular, and RS CVn binaries in general, is the strong and highly variable Ca II H and K and the intermittent H_α emission. In addition to the radio emission, HR 1099 is found to emit both soft and hard X-rays (Walter, Charles and Bowyer 1978; White, Sanford and Weiler 1978). A striking photometric characteristic of

HR 1099 and several other members of its class is the wave-like distortions seen in their light curves.

We observed HR 1099 as part of a photometric programme of RS CVn systems and related objects. The light curves of most of these close binary systems are variable in shape, mean light level, amplitude and phase. Sometimes, dramatic changes occur in their light curves in a time as short as a few orbital periods. The nature and the timescales of such changes should be known for a comprehensive treatment of any model which would accommodate all the observed peculiarities. In this paper we present new *UBV* photometry of HR 1099 and discuss the aspects of distribution and nature of spots on the surface of the active component.

2. Observations

Observations were made with the 34-cm Cassegrain reflector of the Kavalur Observatory through filters chosen to match the standard *UBV* photometric system. During the 1979–80 season we observed HR 1099 on 38 nights between November and March while during the 1980–81 season observations were made on 24 nights between November and March. The faint visual companion (ADS 2644B, K3 V) was included in all the observations. The measurements were made differentially with respect to the comparison star 10 Tau and were transformed to the Johnson system. Tables 1 and 2 contain the resulting standard differential magnitudes and colours of HR 1099. Each value given in the tables is a mean of three or four independent measurements. The Julian days of observation were converted into orbital phases with the following ephemeris (Landis *et al.* 1978):

$$\mathrm{JD} = 2442766{\cdot}069 + 2^{\mathrm{d}}{\cdot}83782\,E.$$

The observations listed in Tables 1 and 2 are plotted in Figs 1 and 2 respectively.

Fig. 1 which is the plot of the 1979–80 observations reveals a nearly sinusoidal light variation with an amplitude of about 0·15 mag. Both the maximum and minimum of the light curve are clearly defined and occur at phases close to 0·5 and 0·9 respectively. The light curve obtained during the 1980–81 observing run, plotted in Fig. 2, is drastically different from that of the previous season in all details. It is highly asymmetric with two unequal maxima, both of them flat-topped. The total amplitude of the light variation is only $\sim$0·08 mag. On one occasion during the 1980–81 season—namely JD 2444673·092 – the star was brighter by $\sim$0·05 mag compared to the expected mean light level. The system was slightly brighter than the expected mean light level on the previous night also.

The $U - B$ and $B - V$ colours do not show any significant correlation with the light variation. They appear scattered about their respective mean values. The typical uncertainty in the differential magnitudes given in Tables 1 and 2 is $\sim$0·01 mag; hence the comparatively large scatter seen in Figs 1 and 2 is intrinsic to the star and indicates that fluctuations on a short timescale are present in the brightness of HR 1099.

Table 1. The differential magnitudes and colours of HR 1099 obtained during the 1979–80 season.

JD 2444000+	ΔV	$\Delta (B-V)$	$\Delta (U-B)$
207·260	1·581	0·390	0·441
208·298	1·536	0·371	0·444
209·299	1·506	0·394	0·416
210·287	1·620	0·399	0·414
226·224	1·426	0·358	0·431
229·254	1·430	0·378	0·431
230·275	1·558	0·376	0·444
237·147	1·448	0·366	0·450
238·147	1·499	0·380	0·457
240·229	1·444	0·379	0·452
241·194	1·533	0·376	0·458
244·218	1·546	0·379	0·415
245·161	1·509	0·372	0·469
249·237	1·472	0·384	0·463
251·199	1·480	0·355	0·483
253·227	1·569	0·371	0·458
254·232	1·451	0·371	0·445
255·124	1·514	0·386	0·459
258·152	1·518	0·367	0·443
259·169	1·527	0·381	0·446
261·142	1·570	0·392	
261·172	1·546	0·388	
261·199	1·545	0·367	
261·225	1·542	0·380	
263·209	1·463	0·376	0·456
264·177	1·575	0·377	0·454
266·202	1·472	0·385	0·465
271·222	1·435	0·370	0·435
273·146	1·553	0·393	
274·155	1·450	0·405	0·478
275·157	1·533	0·366	
276·112	1·528	0·397	
278·114	1·594	0·367	0·410
279·109	1·512	0·385	0·444
282·114	1·567	0·347	0·440
290·096	1·575	0·377	0·445
298·105	1·598	0·363	0·435
299·124	1·522	0·385	0·447
303·096	1·492	0·384	0·438
315·098	1·545	0·346	0·451
322·088	1·525	0·372	0·471

Table 2. The differential magnitudes and colours of HR 1099 obtained during the 1980–81 season.

JD 2444000+	Δ V	Δ $(B-V)$	Δ $(U-B)$
571·408	1·582	0·359	0·420
610·195	1·544	0·379	0·417
611·202	1·571	0·366	0·431
616·175	1·552	0·356	0·408
618·165	1·543	0·393	0·419
619·185	1·579	0·367	0·409
632·177	1·581	0·368	0·410
633·214	1·589	0·371	0·386
634·163	1·568	0·351	0·427
635·164	1·574	0·380	0·401
636·126	1·605	0·375	0·394
639·164	1·581	0·383	0·405
645·094	1·593	0·363	0·432
646·084	1·589	0·380	0·409
647·094	1·560	0·376	0·430
660·113	1·617	0·380	0·409
667·094	1·539	0·340	0·405
668·091	1·589	0·378	0·422
670·089	1·559	0·364	0·396
671·095	1·564	0·358	0·435
672·090	1·524	0·369	0·446
673·092	1·525	0·356	0·424
677·080	1·608	0·360	0·418
678·088	1·539	0·356	0·396

3. Discussion

To account for the unusual photometric behaviour of the RS CVn type systems various models have been proposed and the explanation in terms of surface activity in the form of spots has received the strongest support from the observations, mainly from the wide band photometry (Eaton and Hall 1979). According to this model, starspots which are distributed unevenly on the cooler (and generally more massive) component modulate the observed light as the star rotates, causing the ‘wave-like distortion’ in the light curve. The changes in the light curve are attributed to the changes in the locations and distribution of spots on the stellar surface. In their spectroscopic study of HR 1099 Ramsey and Nations (1980) found that when the star was at light minimum the TiO *R* branch band-head near 8860 Å dramatically appeared or strengthened while the same was absent in the spectra taken during the light maximum. This means that the hemisphere visible at the light minimum is cooler than the hemisphere visible at the light maximum. Assuming a spectral type K0 for the normal photosphere of the cooler component of HR 1099, Ramsey and Nations found that the spots are cooler than the photosphere by about 1000 K. In what

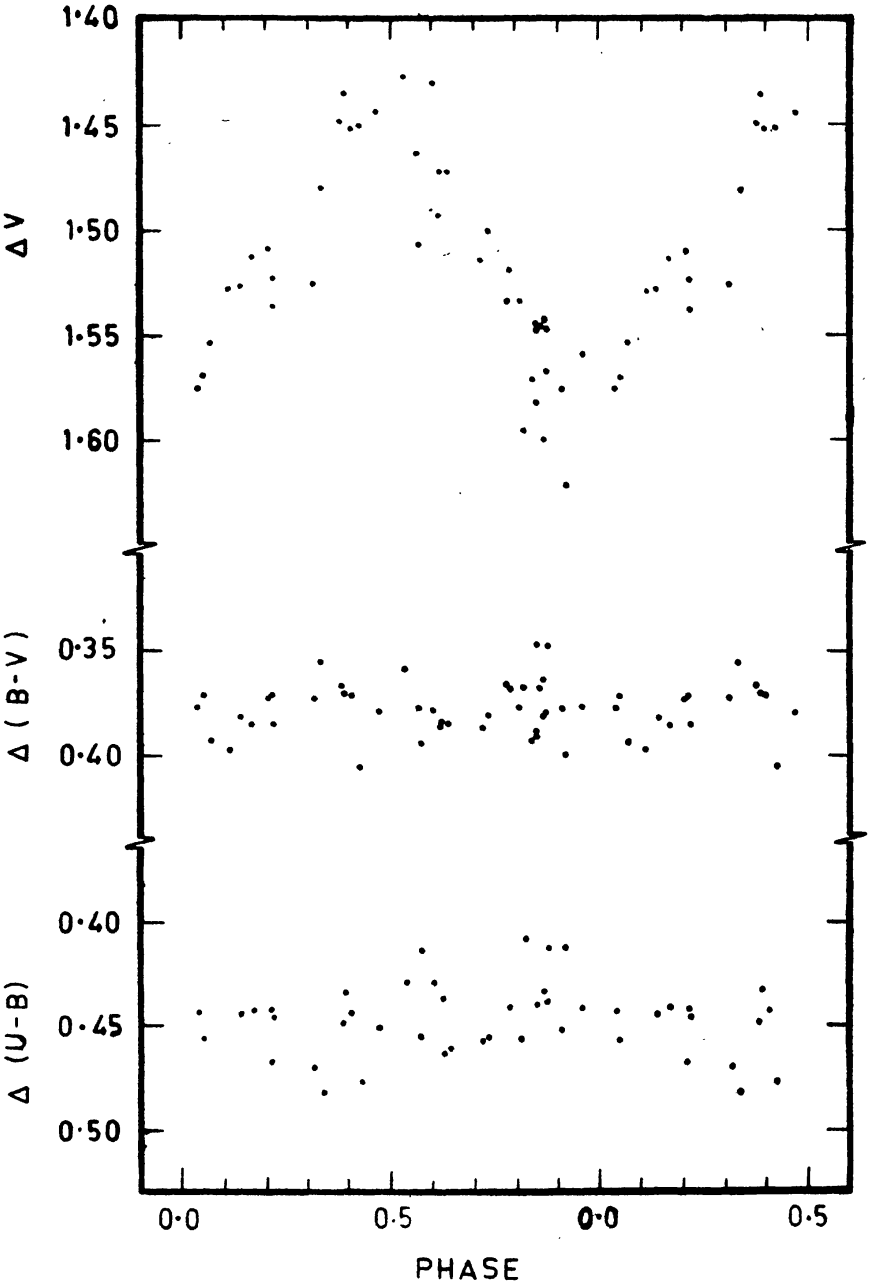

Figure 1. V, $B-V$ and $U-B$ light curves of HR 1099 obtained during the 1979–80 season.

follows we discuss the implications of the photometric properties of HR 1099 on the nature and the distribution of spots on the surface of the active component.

3.1 *Brightness at the Light Maximum and Minimum*

Several quantities are tabulated in Table 3 for different epochs: the observed maximum and minimum brightness of HR 1099, the amplitude of light variation in the visual band and the phase of light minimum together with its extent over the orbital

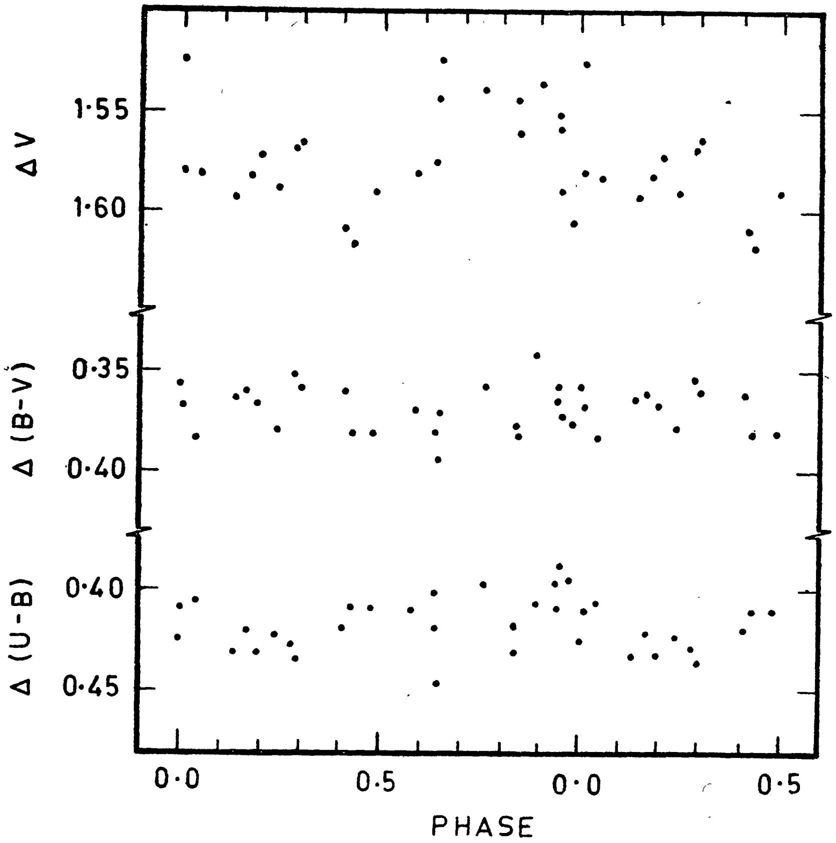

Figure 2. *V*, *B*–*V* and *U*–*B* light curves of HR 1099 obtained during the 1980–81 season.

Table 3. Wave amplitudes, the brightness at light maxima and minima, and the phases of the light minima.

JD 2440000+ Interval	JD 2440000+ Mean	Amplitude	Δ*V* Maximum	Δ*V* Minimum	Phase Minimum	Reference
2720–2729	2724	0·095	1·525	1·620	0·59 ± 0·15	1
2749–2776	2762	0·115	1·490	1·605	0·63 ± 0·05	1
2780–2809	2794	0·135	1·465	1·595	0·63 ± 0·05	1
2813–2838	2826	0·090	1·495	1·585	0·54 ± 0·07	1
3041–3070	3056	0·115	1·495	1·610	0·57 ± 0·07	2
3081–3131	3106	0·120	1·500	1·620	0·63 ± 0·05	2
3176–3216	3196	0·115	1·495	1·610	0·55 ± 0·11	2, 3
3396–3437	3416	0·110	1·500	1·610	0·60 ± 0·07	4
3485–3537	3506	0·085	1·505	1·590	0·70 ± 0·10	4
3561–3590	3576	0·072	1·520	1·592	0·72 ± 0·08	5
3908–3953	3930	0·210	1·415	1·625	0·91 ± 0·06	6
4207–4258	4232	0·170	1·430	1·600	0·92 ± 0·07	7
4259–4322	4290	0·155	1·440	1·595	0·86 ± 0·07	7
4610–4636	4623	0·053	1·542	1·595	0·02 ± 0·08 0·53 ± 0·07	7
4639–4678	4658	0·085	1·530	1·615	0·12 ± 0·08 0·43 ± 0·05	7

References:

1. Bopp *et al.* (1977) 2. Landis *et al.* (1978) 3. Parthasarathy, Raveendran and Mekkaden (1981) 4. Bartolini *et al.* (1978) 5. Chambliss *et al.* (1978) 6. Chambliss and Detterline (1979) 7. Present study

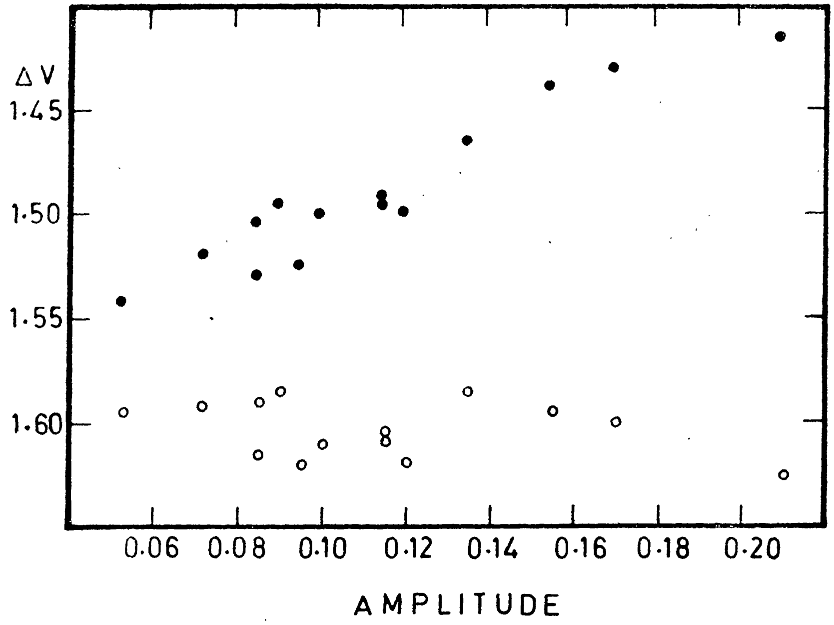

Figure 3. Brightness of HR 1099 at the light maximum (filled circle) and light minimum (open circle) plotted against the wave amplitude.

phase. The only criterion taken into account while subdividing the observations into different groups was that the data contained in each group defined the mean light curve adequately. All the available individual measurements made differentially with respect to the comparison star 10 Tau were considered. The quantities given in Table 3 were evaluated from graphical plots of the observations; the extent of the light minimum refers to the fraction of the orbital phase over which the minimum brightness remains more or less the same, and the amplitude is the difference between the values of $\Delta V_{\max}$ and $\Delta V_{\min}$. Fig. 3 shows the plots of the $\Delta V_{\max}$ and $\Delta V_{\min}$ values against the corresponding amplitudes. A part of the scatter seen in the figure is possibly due to the inconsistencies in the transformation from the various instrumental systems to the standard *UBV* system.

If we assume in analogy with sunspots, that the spots responsible for the distortion wave in the light curve are dark, then the spots would be more predominant on the hemisphere visible at the light minimum. An inspection of Fig. 3 shows that the observed brightness of HR 1099 at light minimum is more or less constant within the observational uncertainties; this implies that the hemisphere of the active component which is visible at the light minimum is always nearly ‘ saturated ’ with spots, the fluctuations that might be present being small. We also find in Fig. 3 that the increase in wave amplitude is directly related to an increase in the brightness of HR 1099 at light maximum. It follows that, when the amplitude is small, a substantial fraction of the stellar surface is covered by spots and the increase in the amplitude is a consequence of the disappearance of spots from the stellar surface. The possibility of the spots drifting towards the invisible circumpolar region seems most unlikely. In the case of the sun we know that during maximum activity the fractional area covered by the spots is also a maximum. On the same grounds we find that in the case of

HR 1099 a smaller amplitude for the light variation means that the star is comparatively more active.

3.2 *Wave Amplitude and Phase of the Light Minimum*

In Fig. 4 the amplitude of the light variation in the visual band and the phase of light minimum ($\phi_{\min}$) are plotted against the mean epoch of observation. In addition to the values given in Table 3 the results of Dean (1979) and Antonopoulou and Williams (1980) are included. The length of the vertical line indicates the extent of the light minimum over the orbital phase. It is interesting to see that there is some correlation between the changes in the amplitude and phase of the light minimum. One of the details usually used to describe the light curve is the $\phi_{\min}$ determined by fitting the light curve with the truncated Fourier series $l = A_0 + A_1 \cos\theta + A_2 \cos 2\theta + B_1 \sin\theta$ (Sarma and Ausekar 1980; Rodonó 1981). In most cases the minimum of the light curve covers an appreciable fraction of the photometric period. Further, the $\phi_{\min}$ derived from the truncated series would be affected by the distribution of observations over the photometric phases, especially when the light curve shows large asymmetry. Hence it is difficult to attach any significant meaning to the $\phi_{\min}$ and the corresponding errors thus determined. If we consider the total extent

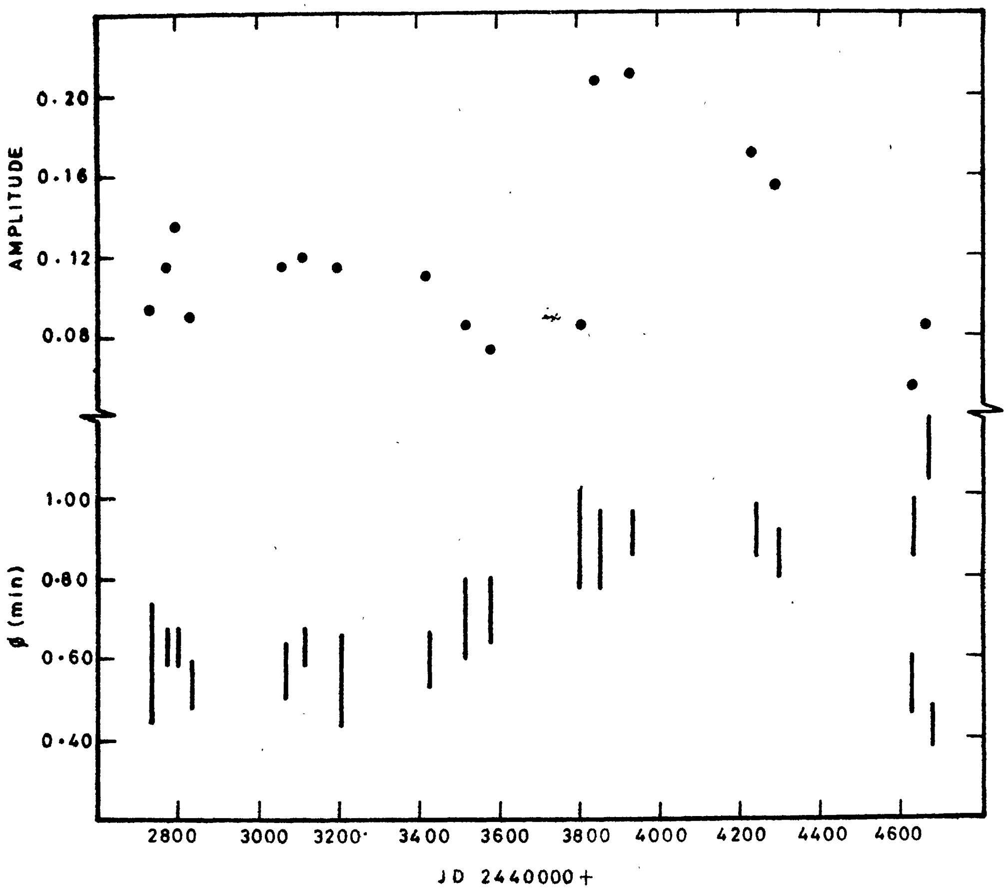

Figure 4. Plot of wave amplitude and phase of light minimum against the mean epoch of observation. The length of the vertical line indicates the extent of the light minimum over the orbital phase.

of the light minimum, instead of the value of $\phi_{\min}$ alone, the observations till JD 2444600 could be represented by two straight line portions parallel to the JD-axis. This would mean that from JD 2442700 to JD 2443800 spots were predominant more or less on the same hemisphere without any significant migration. But small-scale random fluctuations both in the extent and longitude of the ' centre of activity ' were present. Following the rather sudden increase in the wave amplitude, the longitude of the centre of activity also shifted abruptly and remained nearly the same till JD 2444600 when another region of activity developed around a different longitude as evidenced by the two light minima exhibited by the light curve obtained during the 1980–81 season. This is contrary to the observations of the earlier epochs which always showed only one light minimum. It is evident that the available photometric information on HR 1099 does not give any clear-cut indication regarding the continuous migration of the photometric wave ascribed to it by several investigators (Landis *et al.* 1978; Sarma and Ausekar 1980; Rodonó 1981). In fact what we see is the abrupt change of the location of the activity-centre to some arbitrary longitude rather than its systematic drift over the longitude.

The light curve of HR 1099 exhibits more asymmetry when the amplitude is lower indicating that the distribution of the spots is more uneven when the fractional area covered by the spots is higher. Fig. 4 strongly suggests that when a substantial fraction of the stellar surface is occupied by spots, as evidenced by the low wave amplitude, through some phenomena which occur over comparatively short lengths of time a large fraction of the spots disappear from a hemisphere. Such events seem to have occurred around JD 2443820 causing major changes in the amplitude and phase of the light curve. There is some indication that the variation of the wave amplitude is quasi-periodic with a period around 5–6 yr. From Fig. 4 it is apparent that the wave amplitude rises to a comparatively high value in a time as short as thirty days or still shorter and subsequently falls off at a much slower rate. A similar trend has been observed in the wave amplitude of the well known RS CVn binary system RT Lac (Shore and Hall 1980).

3.3 *Photometric Wave and Chromospheric Activity*

It is well known that active regions on the sun are associated with spots and hence if the starspots invoked to explain the photometric peculiarities of HR 1099 are analogous to sunspots, we should expect chromospheric emission to be correlated with the light variability. In fact spectroscopic studies of HR 1099 by Nations and Ramsey (1980) and Ramsey and Nations (1980) did show that the equivalent width of H_α emission undergoes a modulation over the photometric cycle. But Bopp and Talcott (1978) have reported that their spectroscopic observations of HR 1099 do not indicate any consistent correlation of H_α equivalent width with the light variability. From Fig. 3 it is clear that the available photometry does not provide a ' saturation value ' for the brightness at light maximum and hence, it follows that the spots were present nearly all over the stellar surface with the maximum concentration on the hemisphere visible at the light minimum. Sporadic emission from the active regions associated with the starspots might mask the modulation of the equivalent width of H_α over the photometric phase, especially when the amplitude is comparatively low and the observations are spread over a larger number of photometric cycles. Photometric studies of HR 1099 by Parthasarathy, Raveendran and Mekkaden (1981) have shown that significant changes in the light curve sometimes occur within a couple of orbital periods. Hence it is conceivable that large-scale changes in the distribution of spots could take place in a few photometric cycles. The observations of Nations and Ramsey were confined to only six consecutive nights while those of Bopp and Talcott were spread over more than two years.

3.4 *The Nature of Spots and the Model of Dorren and Guinan*

The photometric study of BY Dra by Oskanyan *et al.* (1977) has shown that the nature of spots —*i.e.* bright or dark—invoked to explain the photometric peculiarities depends on the choice of the brightness of the unspotted photosphere. If we invoke bright spots to explain the unusual photometric behaviour of HR 1099, then from Fig. 3 it follows that the constant brightness observed at the light minimum corresponds to the brightness of the unspotted photosphere and increase in the amplitude is directly related to the increase in the fractional area occupied by the bright spots. The situation when the wave amplitude is high corresponds to the case when the star is at its maximum activity. We know that the strong Ca II H and K and H_α emission indicates the presence of a chromosphere around the cooler component. The bright facular regions could heat the overlying chromosphere producing the observed enhanced emission. In this case one would expect the H_α emission equivalent width to vary in phase with the photometric wave since more bright spots would be facing the observer at the light maximum. However, spectroscopic data of HR 1099 (Nations and Ramsey 1980) show that the variations in the light and equivalent width of H_α emission are anticorrelated. Further, large bright surface inhomogeneities are expected to produce appreciable colour variation (Torres and Ferraz Mello 1973), while in the case of HR 1099 $B - V$ and $U - B$ show no significant correlation with the light variability. These results conclusively rule out the possibility that bright spots cause the observed light variation. We suggest that dark spots similar to sunspots should be preferred; the cooler and darker starspots reduce the continuum emission while the associated plage-like regions give rise to the enhanced emission. The available photometric information does not indicate a saturation value for the brightness at light maximum; this implies that spots did not disappear completely from the field of view. Hence, it is evident that on the assumption that the spots are dark, it is difficult to assign any brightness to the unspotted photosphere from the available photometry.

In the recent analysis of the long-term photometric behaviour of HR 1099, Dorren and Guinan (1982) have tried to interpret the rather complicated changes in the light curves in terms of a simple two-spot model. The spots were assumed to be of circular shape and of equal size and cooler than the photosphere by $\sim$ 1800 K. They found that the assumed two-spot model could reproduce all the diverse light curves of HR 1099. They also found a strong dependence of the amplitude on the spot size. Their results are plotted in Fig. 5. It is clearly seen that, when the wave amplitude tends to zero, their computations predict almost a spot-free component whose brightness should correspond to the maximum observed brightness. Such a conclusion is contrary to the observational results plotted in Fig. 3, where we find that a decrease in the amplitude of the light variation is followed by a decrease in the brightness of the star.

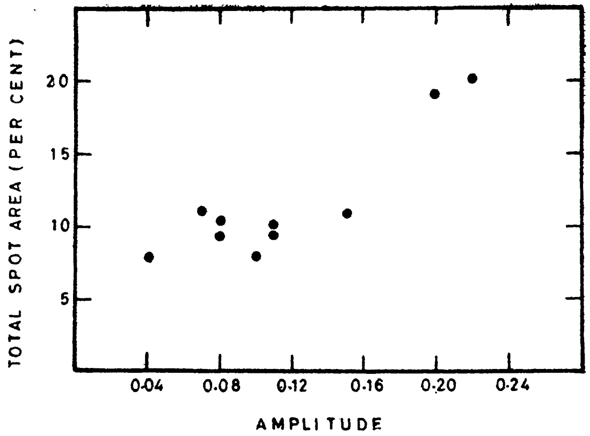

Figure 5. Plot of total spot-area against the wave amplitude (based on Dorren and Guinan 1982).

4. Conclusions

UBV photometry of HR 1099 shows that during the 1979–80 observing season the amplitude of light variation was ~ 0·15 mag whereas during 1980–81 season it was only ~ 0·08 mag. The two light curves are found to differ drastically in all respects.

Depending on the choice of the brightness of the unspotted photosphere either bright or dark spots could be invoked to explain the distortion wave in the light curve of HR 1099. The available spectroscopic information shows that variations in the light and equivalent width of H_α are anticorrelated. In addition, no significant colour variation is seen during the photometric cycle. For these two reasons, we point out, that dark spots analogous to sunspots should be preferred to explain the wave-like distortion in HR 1099.

Because it is found that the brightness of HR 1099 at maximum is linearly dependant on the wave amplitude, while the brightness at the light minimum remains nearly constant, it follows that there is always a hemisphere of the active component which is ‘ saturated ’ with spots.

The light curve of HR 1099 is seen to exhibit more asymmetry when the amplitude is lower. It is seen that a change in the amplitude of light variation from a low to a high value can occur in a time as short as thirty days. The variation of the wave amplitude seems to be quasi-periodic with a period around 5–6 yr. The present study shows that the available photometry does not provide any clear-cut evidence confirming continuous migration of the photometric wave ascribed to it by several different investigators.

The two-spot model proposed by Dorren and Guinan (1982) is found to be inadequate to account for all the observed photometric characteristics. The problems associated with spot modelling have been discussed already in detail by Rodonó (1980). The independent parameters involved in the modelling are locations of the spotted regions, extent of spots in both longitude and latitude, spot temperature and above all the brightness of the unspotted photosphere. In the case of the non-eclipsing systems the orbital inclination appears as yet another independent parameter. In practice it is difficult to obtain a unique set of solutions, even though excellent reproductions of the observed light curves can be obtained by suitably adjusting the above parameters. Though the spot model is the most promising working hypothesis, all the observational constraints, both spectroscopic and photometric, should be available and well-defined for a comprehensive treatment of the model.

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