5

YOUNG ACTIVE-CHROMOSPHERE OBJECTS

5.1. HD 139084

5.1.1. Introduction

HD 139084 (= V343 Nor) displays strong Ca II H & K and filled-in Hα emissions (Bidelman & Maconnell 1973; Bopp & Hearnshaw 1983). The star has also been found to show emission at microwave frequencies (Slee et al. 1987). It was initially classified as a member of BY Draconis type stars on the basis of the nature of its light variation and strong chromospheric emission. Houk & Cowley (1975) had suggested earlier that the broadband colours are probably composite and had assigned spectral types K1 III and F for the components of HD 139084. However, the radial velocity measurements by Balona (1987) did not show any variations, confirming the star as single. Later, Pallavicini et al. (1992) reported that the Li I 6708 Å absorption line present in the spectrum of HD 139084 is much stronger than the nearby Ca I 6717 Å absorption line. Randich et al. (1993) proposed that the extremely high Lithium abundance (n(Li) = 3.6) in HD 139084 could be due to it being a young pre-main sequence object. Consolidating the data on the proper motions, rotational Vsin_i and radial velocities, Anders et al. (1991) concluded that HD 139084 belongs to the Pleiades super cluster, which
indicates an age of 7–10 x 10^7 years, consistent with the derived Lithium abundance. They also estimated a distance of 55 pc to the star, which they find implies an M_V (= 4.3 mag) much brighter than that expected from its K0 V spectral classification.

The light variability of HD 139084 was discovered by Udalsky & Geyer (1985) who derived a 4.2 day photometric period. The light curve which they obtained showed two minima and an amplitude of 0.15 mag. Bopp et al. (1985), who obtained additional photometry of HD 139084, found that their data also showed a similar photometric period, and based on the U – B colour observed they suggested that the components are of spectral types K1 III and F. The nonvariability of radial velocity was attributed to a very low orbital inclination by them. But in such a case the light variability due to rotational modulation is expected to be negligible. The shape of the light curve which Bopp et al. (1985) obtained was similar to that obtained by Udalsky & Geyer (1985) one year earlier. The observations of Cutispoto (1990) during February 1987 showed that the maximum of the V light curve was about 0.06 mag brighter than its previously observed values. From an analysis of the observations during February–March 1989, Cutispoto (1993) found that a period of 4.56 days gives a better fit to his observations than the previously reported period of 4.2 days. Photometry of HD 139084 obtained by Anders et al. (1991) during 1990 showed an amplitude of 0.16 mag in V, which is the highest amplitude so far observed.

5.1.2. Photometry

HD 139084 was observed on a total of 45 nights over four seasons: 1987 (12 nights), 1988 (12 nights), 1989 (11 nights) and 1990 (10 nights). UBVRI photometry was carried out during the first two seasons and V photometry during the remaining two seasons. The observations were restricted to V bands during 1989 and 1990 due to the low photon flux of the star at shorter wavelengths. The comparison stars were SAO 242701 and SAO 242788, and all the observations were made differentially with respect to SAO 242701. Several observations were made each night and averages were taken after grouping them into two or three. Table 1 gives the mean UBVRI magni-
tudes of SAO 242701 and SAO 242788 and by magnitudes of the former. The differential quantities of HD 139084 were converted to $UBVRI$ and by magnitudes using the corresponding values of SAO 242701 given in Table 1 and are tabulated in Tables 2 and 3.

Table 1. $UBVRI$ and $b$ magnitudes of the comparison stars of HD 139084

<table>
<thead>
<tr>
<th>Star</th>
<th>$U$</th>
<th>$B$</th>
<th>$V$</th>
<th>$R$</th>
<th>$I$</th>
<th>$b$</th>
<th>$y$</th>
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<td>7.850</td>
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<td>$\pm 0.004$</td>
<td>$\pm 0.004$</td>
<td>$\pm 0.005$</td>
<td>$\pm 0.007$</td>
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<td>SAO 242788</td>
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<td>8.682</td>
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5.1.3. Photometric period

There is no consistency in the photometric period for HD 139084 quoted in the literature. Udalsky & Geyer (1985), for example, reported the photometric period as 4.2 days while Cutispoto (1993) reported the period to be 4.57 days. The discrepancy in the periods quoted could be partly due to the error involved in its determination. When the available observations are a few in number and the observations span over a short time interval, the period finding technique usually would not yield the correct value. The data obtained over a longer duration cannot be combined as in the case of the radial velocity measurements to yield a better period because the light curves in general show appreciable phase shifts and changes in shape as a result of short term fluctuations in the distribution of active regions on the stellar surface. A slight mismatch in the periods derived can also occur because of a difference in the approach adopted in their determination. To eliminate such a possibility, the $V$ and $y$ data given in Table 2 and 3, and the $V$ data available in the literature were analyzed using the method described in § 2.4..
Table 2. $UBVRI$ magnitudes of HD 139084

<table>
<thead>
<tr>
<th>J.D.</th>
<th>$U$</th>
<th>$B$</th>
<th>$V$</th>
<th>$R$</th>
<th>$I$</th>
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Table 2. continued

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</table>

Totally there are 8 sets of data that are suitable for a period determination. They are listed in Table 4 along with their sources. The quantity $Q$, taken as the measure of scattering in the phase-magnitude plot, shows a flat minimum.
in most cases because of the small number of photometric cycles covered in each case. The errors in the period listed in Table 4 refer to the half-width of the flat minimum. The comparatively large errors arise because of the low amplitudes of light variation and the short data lengths.

Table 3. by magnitudes of HD 139084

<table>
<thead>
<tr>
<th>J.D.</th>
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</tr>
<tr>
<td>8094.510</td>
<td>8.619</td>
<td>8.100</td>
</tr>
</tbody>
</table>
The Julian days of observation given in Table 2 and 3 were converted to photometric phases using the following ephemeris:

\[ JD (Hel.) = 2446898.8 + 4.294 E, \]

where the initial epoch corresponds to the light minimum observed in the present 1987 data and the period is the average of the periods given in Table 4. The \( V \) magnitudes and \( U - B \), \( B - V \), \( V - R \), and \( V - I \) colours are plotted in Figures 1 and 2, and \( y \) and \( b - y \) in Figure 3. The corresponding mean epochs of observation are also indicated in the figures.

HD 139084 has been observed on nine occasions during the years 1981 to 1990. In order to study the long-term photometric behaviour all these observations were replotted with the above ephemeris, and the values of
Fig. 1. Plots of $V$, $U - B$, $B - V$, $V - R$ and $V - I$ of HD 139084
Fig. 2. Plots of V, U-B, B-V, V-R and V-I of HD 139084
Fig. 3. Plots of $y$ and $b-y$ of HD 139084
$V_{max}$, $V_{min}$, $\phi_{min}$ and the amplitudes were read out directly from the plots of the light curves and are given in Table 5. The amplitude observed is generally not large; usually it is less than 0.10 mag. The highest amplitude so far observed is $\sim 0.16$ mag (Anders et al. 1991). During three epochs the

Table 4. Photometric periods derived from various sets of data

<table>
<thead>
<tr>
<th>Mean epoch</th>
<th>J D interval</th>
<th>Cycles covered</th>
<th>Period</th>
<th>Reference</th>
</tr>
</thead>
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<td>1981.50</td>
<td>4767-4806</td>
<td>9.1</td>
<td>4.38±0.12</td>
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<td>1984.30</td>
<td>5805-5815</td>
<td>2.3</td>
<td>4.26±0.16</td>
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<tr>
<td>1985.43</td>
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<td>1.9</td>
<td>4.10±0.08</td>
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<td>4.30±0.09</td>
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<td>7296-7315</td>
<td>4.4</td>
<td>4.39±0.04</td>
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<td>1989.16</td>
<td>7577-7595</td>
<td>4.2</td>
<td>4.48±0.17</td>
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<tr>
<td>1989.61</td>
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<td>4</td>
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<td>8088-8103</td>
<td>3.5</td>
<td>4.18±0.12</td>
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</tr>
</tbody>
</table>

(1) Lloyd Evans 1987; (2) Udalasky & Geyer 1985; (3) Bopp et al. 1986; (4) Present study; (5) Cutispoto 1993

light curves showed double minima, if interpreted as due to spot activity suggests the presence of two prominent active regions well separated in longitudes at these epochs. The light curves obtained during 1988.39 (present study) and 1981.5 (Lloyd Evans 1987) are similar in amplitude and shape. Most probably, the spot groups at these epochs, though located at different longitudes, had similar spot coverage and spot temperature. As explained later in § 5.1.6. earlier the spots also had similar latitudes, below the equator as seen by the observer.

5.1.5. Brightness at light maximum and minimum

Figure 4a is a plot of $V_{max}$ and $V_{min}$ of HD 139084 given in Table 5 against
the corresponding epoch of observation. The extent of the vertical bar gives the amplitude corresponding to that epoch. An inspection of the figure shows that the brightest $V_{\text{max}}$ so far observed is 7.995 mag. This probably corresponds to the unspotted magnitude. Neither the amplitude nor the brightness at light maximum and minimum do gives directly any idea on

Table 5. Photometric characteristics of HD 139084

<table>
<thead>
<tr>
<th>Epoch</th>
<th>Amplitude</th>
<th>$V_{\text{max}}$</th>
<th>$V_{\text{min}}$</th>
<th>$\phi_{\text{min}}$</th>
<th>References</th>
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<td>8.055</td>
<td>8.090</td>
<td>0.55</td>
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</tr>
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<td>1984.30</td>
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<td>0.70</td>
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<td>Bopp et al. (1986)</td>
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<td>1987.28</td>
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<td>0.00</td>
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</tr>
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<td>1988.39</td>
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<td>8.255</td>
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<td>0.95</td>
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</table>

spot coverage on the stellar surface. The amplitude is only a measure of the longitudinal asymmetry in the spot distribution. A comparison of the brightness at light maximum and minimum observed at two different epochs would give an indication of the relative spot coverage on the stellar surface. Since the star is viewed at a low inclination ($i \sim 40^\circ$, § 5.1.6.), spots that occur at high latitudes would appear as circumpolar and hence would not contribute to the light modulation appreciably, and hence the amplitude essentially gives the spot distribution about an equatorial belt whose width depends on the inclination. The $V_{\text{max}}$ observed during 1984.30 was fainter than the $V_{\text{max}}$ observed during 1981.50 by only $\sim 0.02$ while $V_{\text{min}}$ observed
during the former occasion was about 0.10 mag fainter than that observed during the latter. This indicates that the spot coverage on the hemisphere visible at light minimum was higher on the former occasion than that on the latter, while the spot coverage on the hemisphere seen at light maximum during the two occasions remained nearly the same. The $V_{\text{min}}$ observed during 1987.11 was close to the $V_{\text{max}}$ observed during the previous occasion, i.e., during 1985.43, which means that the hemisphere visible at light minimum during the former occasion had only a spot coverage similar to that of the hemisphere visible at light maximum at the latter epoch, indicating that the overall spot coverage during 1987.11 was significantly less than that during 1985.43. Therefore there was an overall increase in the spot coverage from 1981 till around 1985 which then decreased and became a minimum sometime around 1987. By a similar argument it follows that there was a near-continuous increase in the spot coverage on the stellar surface from 1987.11 onwards till 1990.58. During 1990 the star was at its maximum activity level, indicated by a low $V_{\text{max}}$ and the extreme $V_{\text{min}}$ observed till that epoch. The trend in Fig 4a suggests a period around 10 years for an activity cycle.

Figure 5 is a plot of $V_{\text{max}}$ and $V_{\text{min}}$ from Table 5 against the corresponding amplitudes. The $V_{\text{min}}$ shows a larger range when compared to $V_{\text{max}}$. It is clear that on most occasions HD 139084 exhibits an amplitude less than 0.1 mag. The amplitude seems to be correlated with the brightness at light minimum, in the sense that at higher amplitudes the brightness at light minimum is fainter. There is no correlation between the amplitude and the brightness at light maximum.

5.1.6. Phase of light minimum

From Table 4 it is seen that the photometric period derived from the data obtained during different seasons varies from 4.10–4.50 days, with a mean period of 4.294±0.043 days. It is tempting to conclude that the differences, at least partly, arises from the differential rotation that is expected in a late-type star. If the starspots have a large latitudinal extent, establishing the differential rotation from the photometric data would be rather difficult.
Fig. 4. Plots of (a) Vmax (open circles) and Vmin (filled circles) and (b) phase min. against the corresponding mean epoch.
Fig. 5. Plots of $V_{\text{max}}$ (open circles) and $V_{\text{min}}$ (filled circles) against the corresponding amplitude.
because the photometric period would then correspond to the rotational period of the effective latitude of spot distribution. However, if spots that produce the rotational modulation are confined mostly to a narrow latitudinal belt at a particular epoch the photometric period derived would refer to the rotation period at that latitude. Hence, if the spots are predominantly present selectively at different latitudes at different epochs the photometric periods derived would show a range of values as a result of differential rotation.

The light curves obtained during 1981.50 and 1988.39 are similar in all respects; both light curves show flat maxima extending over more than 0.05, and narrow light minima with depths around 0.03 mag. The above characteristics are possible for the light curves if the modulating spots disappear completely from the field of view for a substantial fraction of the rotational period, and this in turn is possible only if the corresponding spot groups had a large polar distance, measured from the pole above the sky plane. Anders et al. (1991) find that the Rsini and the space velocity (U, V, W) observed are consistent with an inclination i = 40° for the rotational axis, and hence the main contribution to the light modulation will come from spots within a ±40° latitudinal belt. Therefore it appears that the spots which produce the rotational modulation at the above two epochs were situated at the highest visible stellar latitudes below the equator as seen from the pole above the sky plane. Definitely spots were present at other locations on the stellar surface at these epochs because the light maximum was below its maximum value so far observed. Here it may be noted from Table 4 that the photometric periods derived for these two epochs are longer than all the other periods except one, corresponding to the epoch of 1989.16. This together with the above conclusion that the corresponding spot groups were predominantly located at the highest visible latitudes suggests that higher latitudes are rotating slower, as expected from the differential rotation that is characteristic of a late-type star. During 1989.16, when the photometry showed the largest period (4.48 days), the light curve showed a near-sinusoidal shape indicating that the spots never disappeared completely from the line of sight. This could happen if spots were situated near the circumpolar region above the
An investigation of the behaviour of the phase of light minimum can also provide some information on the differential rotation of the star. If there is only one prominent spot group on the star then the phase of the light minimum is an indicator of the location of spot group that cause the modulation of light. In Figure 4b the values of $\phi_{\text{min}}$ given in Table 5 are plotted against the corresponding epochs of observation. It is interesting to see that all the deep minima observed so far lie in a near-straight line, indicating that the effective longitude of the spot groups which produce the light modulation did not suffer any sudden change as a result of the formation of new spot groups, or the strengthening of the spot groups already existing at a different longitude. Since the migration is towards the decreasing photometric phase the actual period is slightly less than the mean photometric period of 4.294 days assumed in the folding of the observations. A least square fit to the times of minima gives the best fit photometric period as $4.2792 \pm 0.0004$ days. This corresponds to the rotational period of the equatorial belt which is involved in the light modulation.

If the differences in the photometric periods given in Table 4 is real, at least partly, then the phase of light minimum would not show the type of smooth migration as seen in Figure 4b. Further, The shapes of the light curves obtained during 1984.30 and 1985.43 are nearly identical suggesting that the major changes in the spot distribution did not occur even in about 90 intervening photometric cycles, and hence the modulating spot group did not get drawn out because of the differential rotation. This could happen if the spots were confined to a very narrow latitudinal belt, which is unlikely on account of the comparatively large amplitude of light variation observed, or if the spots in general do not take part in the differential rotation experienced by the star. Here it may be noted that the latitudinal belt that is actually involved in the light modulation is itself quite small since the star is seen at a low inclination, and therefore the range in photometric periods expected from a temporal distribution of spot latitudes may not be appreciable. It
is most likely that the differences in photometric periods seen in Table 4 reflects only the uncertainty involved in their determination and not the differential rotation experienced by the star, and the photometric period of 4.2792±0.0004 day is the rotational period of the star.

From Figure 4b it is seen that during three epochs there were two prominent spot groups well separated in longitudes as indicated by two minima in the light curves. The two minima observed during the epoch 1984.30 were present in the light curve obtained a year later, indicating that the active regions might last longer than a year or so.

Further frequent photometry over several seasons are necessary to arrive at a clearer picture.
5.2. HD 155555

5.2.1. Introduction

HD 155555 (= V834 Ara, LDS 587A) is a 1.6817 day period double-lined spectroscopic binary with both components chromospherically active. Bennett et al. (1962) derived the orbital parameters and assigned the spectral types G5 IV and K0 to the components. The star was classified by Stacy et al. (1980) as an RS CVn system on the basis of the presence of strong Ca II H & K and Mg II h & k emissions. HD 155555 shows filled-in Hα emission and strong X-ray emission (Bopp et al. 1986; Walter et al. 1980). From a spectroscopic analysis, Pasquini et al. (1991) found that both components of HD 155555, apart from strong Ca II H & K and Hα emissions, also display strong Li 6708Å absorption in their spectra. By measuring the equivalent widths of the cross correlation dips for the two components they estimated a difference of around 0.90 mag between the hotter and the cooler components in the CORAVEL band. The M-dwarf visual companion (LDS 587B), which is at a separation of 33 arc sec, shows all the characteristics of an active young dMe star. On the basis of the presence of the strong emission lines and the unusually strong Li I line, Pasquini et al. (1991) suggested that the system HD 155555 consists of three coeval pre-main sequence stars of only a few tens of million years old. Further they found that its space velocities U, V and W are consistent with its membership of the young disk population if a distance of 39±9 pc is assumed. Pallavicini et al. (1992) also reported the strong Lithium absorption lines; they derived an abundance of log N(Li) = 3.5 for the cooler component and log N(Li) = 3.9 for the hotter component. Lithium abundance of the order of = 3.0 are usually found in pre-main sequence stars (Basri et al. 1991). Eggen (1995) re-analyzed the space motions and found that HD 155555 belongs to the Pleiades Super cluster. Since even a high spectral resolution study of the M-type companion did not reveal any Li I absorption line, Martin & Brandner (1995) suggested that the binary is in an evolutionary stage intermediate between the T Tauri stars and the Pleiades low mass stars. Slee et al. (1987) detected microwave
mission at 5.0 and 8.4 GHz in HD 155555. A quiescent emission at 843 MHz of the order of 5 mJy was also detected by Vaughan & Large (1987).

The light variability of HD 155555 was suspected because two independent observations performed a decade apart by Stoy (1963) and by Eggen (1978) differed by about 0.16 mag. The optical light variability was confirmed four years later by Collier (1982). Soon after Udalsky & Geyer (1984) reported that the light variation was sinusoidal with an amplitude of 0.08 mag and a period of 1.66 days, nearly the same as the orbital period. They also found that the colour variations, especially in $V - I$, are in phase with the light variation in the sense that the star is redder at the minimum light. Further photometric observations were carried out by Scaltriti & Busso (1984), Bopp et al. (1986), Lloyd Evans & Koen (1987), Collier Cameroon (1987), Rucinski (1988) and Cutispoto (1990, 1993).

5.2.2. Photometry

Photometric observations of HD 155555 were carried out on 35 nights during four observing seasons: 1987 (10 nights), 1988 (5 nights), 1989 (11 nights) and 1990 (9 nights). $UBVRI$ photometry was done during 1987 and 1988 seasons and by photometry during 1989 and 1990 seasons. SAO 253886 and SAO 253824 were used as comparison stars and all observations were done differentially with respect to SAO 253886. Sufficient care was taken to avoid

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the light contamination from the visual companion LDS 587B which is 33 arc sec away. Several measurements were taken each night to obtain a good phase coverage of light variations. The observations were transformed to the respective standard systems. The mean magnitudes of comparison stars are given in Table 6. The differential magnitudes were converted to $UBVRI$ and by magnitudes using the magnitudes of SAO 253886 given Table 6, and are listed in Tables 7 and 8, respectively.

### Table 7. $UBVRI$ magnitudes of HD 155555

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<td>8100.733</td>
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Table 8. continued

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<th>J.D. 2440000.+</th>
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<td>6.888</td>
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<td>8101.743</td>
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<td>7.417</td>
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<td>8102.630</td>
<td>7.427</td>
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<td>8102.687</td>
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</tr>
<tr>
<td>8102.772</td>
<td>7.410</td>
<td>6.903</td>
</tr>
</tbody>
</table>

5.2.3. Light curves

The photometric period of 1.66 days reported by Udalsky & Geyer (1984) is very close to the orbital period determined by Pasquini et al. (1991), and hence for the conversion of Julian days of observation into photometric phases the following ephemeris provided by the latter authors for the radial velocity data were used:

\[ JD(\text{Hel.}) = 2446998.410 + 1.4681652E. \]

The initial epoch corresponds to the time of maximum radial velocity of the brighter component and the period is the orbital period. Figures 6 and 7 are the plots of \( V, U - B, B - V, V - R, \) and \( V - I \) and Figure 8 is the plot of \( y \) and \( b - y \) observations; the mean epochs of observations are indicated in the respective figures.

Starting in 1979 (Lloyd Evans & Koen 1987), HD 155555 has been observed during 11 seasons including the present 4 seasons. The light curve parameters are read directly from the respective graphical plots of the light curves and are listed in Table 9. None of the available light curves, though displays significant asymmetry, shows double minima, indicating a near continuous longitudinal distribution of spots over the stellar surface. The 1980
Fig. 6. Plots of V, U-B, B-V, V-R and V-I of HD 155555
Fig. 7. Plots of V, U-B, B-V, V-R and V-I of HD 155555
Fig. 8. Plots of $y$, $u-y$, $v-y$ and $b-y$ of HD HD 155555
observations of Lloyd Evans & Koen (1987) and 1983 observations of Scaltriti & Busso (1984) were not included in the present analysis because the corresponding light curves are not defined well as a result of poor phase coverage.

Table 9. Photometric characteristics of HD 155555

<table>
<thead>
<tr>
<th>Epoch</th>
<th>Amplitude</th>
<th>V&lt;sub&gt;max&lt;/sub&gt;</th>
<th>V&lt;sub&gt;min&lt;/sub&gt;</th>
<th>φ&lt;sub&gt;min&lt;/sub&gt;</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>1979.70</td>
<td>0.095</td>
<td>6.730</td>
<td>6.825</td>
<td>0.20</td>
<td>Lloyd Evans &amp; Koen (1987)</td>
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<tr>
<td>1981.47</td>
<td>0.070</td>
<td>6.730</td>
<td>6.800</td>
<td>0.20</td>
<td>Lloyd Evans &amp; Koen (1987)</td>
</tr>
<tr>
<td>1984.30</td>
<td>0.080</td>
<td>6.630</td>
<td>6.710</td>
<td>0.15</td>
<td>Udalsky &amp; Geyer (1984)</td>
</tr>
<tr>
<td>1985.43</td>
<td>0.080</td>
<td>6.685</td>
<td>6.765</td>
<td>0.25</td>
<td>Bopp et al. (1986)</td>
</tr>
<tr>
<td>1986.43</td>
<td>0.065</td>
<td>6.715</td>
<td>6.780</td>
<td>0.25</td>
<td>Rucinski (1988)</td>
</tr>
<tr>
<td>1987.15</td>
<td>0.100</td>
<td>6.700</td>
<td>6.800</td>
<td>0.35</td>
<td>Rucinski (1988), Cutispoto (1990)</td>
</tr>
<tr>
<td>1987.28</td>
<td>0.135</td>
<td>6.675</td>
<td>6.810</td>
<td>0.45</td>
<td>Present study</td>
</tr>
<tr>
<td>1988.39</td>
<td>0.070</td>
<td>6.710</td>
<td>6.780</td>
<td>0.95</td>
<td>Present study</td>
</tr>
<tr>
<td>1989.16</td>
<td>0.115</td>
<td>6.765</td>
<td>6.880</td>
<td>0.35</td>
<td>Cutispoto (1993)</td>
</tr>
<tr>
<td>1989.61</td>
<td>0.135</td>
<td>6.740</td>
<td>6.875</td>
<td>0.65</td>
<td>Present study</td>
</tr>
<tr>
<td>1990.58</td>
<td>0.050</td>
<td>6.865</td>
<td>6.915</td>
<td>0.50</td>
<td>Present study</td>
</tr>
</tbody>
</table>

5.2.4. U − B variation

An inspection of Figures 6 and 7 shows that the variations in B − V, V − R and V − I colours are such that the star appears redder at light minimum, as expected when starspots cooler than the ambient photosphere are the causes of the light modulation. The modulation in U − B colour is quite intriguing. It shows a rather large amplitude in Figure 6, almost the same amplitude as that of the V light curve. The photometry presented in earlier chapters shows that when cooler starspots are present the modulation in U − B is much less than that in V. The U − B colour also shows a large scatter in Figure 6, much larger than the observational uncertainty of ~ 0.01 mag, whereas the V light curve is rather smooth. Figure 7 shows a near-out-of-phase variation of U − B.
with respect to the $V$ light curve. The photometry obtained by Udalsky & Geyer (1984) during 1984.30 shows a phase lag between the $U - B$ colour and $V$ light curves. These imply that in addition to the cooler starspots, there are other quasi-permanent surface features which contribute to the $U$ band flux modulation. Bright photospheric plages is a likely candidate. Another possibility is the presence of bright chromospheric emission regions. The $U$ band includes several Balmer lines which may exhibit emission or filled-in emission and $Ca\, H & K$ emissions. During light minimum the photospheric light is reduced and the chromospheric emission become prominent, affecting the measurements in $U$ band significantly, and there by making $U - B$ bluer. The observations obtained by Cutispoto (1990) and Rucinski (1988), which are separated by twenty days, are re-plotted in Figure 9, as open circles and filled circles. The Julian day intervals are also indicated in the figure. The first set of observations lie systematically above the second set in all the plots shown. During the first spell the $U - B$ colour did not show any modulation with phase, whereas during the second it varied almost out-of-phase with the $V$ light curve. It is clear from the figure that the hotter features that cause the additional modulation in $U$ band are rather short-lived when compared to the cooler starspots; this probably accounts for the large scatter in the $U - B$ curve at certain epochs. The $B$ band is also mostly affected, but to a lesser extent. The shorter life-time for these features is further evident when one compares the $U - B$ values plotted in Figure 9 with those plotted in Figure 6; the latter observations were obtained about 25 days after the former. The out of phase $U - B$ curve became nearly in phase with the $V$ light curve within this short time span.

5.2.5. Broadband colours of the components

From a spectroscopic analysis Pasquini et al. (1991) found that the two components of HD 155555 have similar chromospheric activity. They also found that in the CORAVEL passband (3900-5200Å) the hotter component is brighter by about 0.9 mag. Therefore in the $I$ band the contribution to the total light by the cooler component (K0) could be appreciable. In view of the similar chromospheric activity, as indicated by the $Ca\, II \, H & K$,
Fig. 9. Plots of V, U−B, B−V, V−R and V−I of HD 155555
it is reasonable to expect that both the components are light variables. Most of the light variation seen at shorter wavelengths would be due to hotter component, but at longer wavelengths the observed variation would be the combined effect of the two components. In this case one would expect to see a phase shift in the light curves obtained in $B$ and $I$ bands, at least at some epochs. As already seen the $U$ band observations are complicated by the probable presence of photospheric plage-like regions and chromospheric emissions, otherwise $U$ band observations would be better than $B$ band observations. However, no such phase shift is seen between $B - V$ and $V - I$ colour curves in any of the 11 seasons' photometry that exists for HD 155555, implying that either the cooler component is not a light variable or the amplitude of light variation is significantly smaller than that shown by the hotter component. Udalsky & Geyer (1984) had already suggested that the hotter and the brighter component is probably causing the light variability.

The light and colour curves presented in the earlier sections show that an increase in the amplitude of $V$ light curve is always followed by an increase in the amplitudes of colour curves. Assuming a linear relationship between the amplitudes in $V$ and $X - V$ colour, with $X$ representing any spectral band, the total flux observed in $V$ and $X$ bands at time $t$, $F_t^V$ and $F_t^X$, can be written as

$$F_t^V = F_h^V A + F_c^V B$$

and

$$F_t^X = F_h^X A^\alpha + F_c^X B^\beta,$$

where $F_h^V$ and $F_c^V$ are the unspotted (or, alternatively any reference level) $V$ band flux of hotter and cooler components, $A$ and $B$ are the reduction in $V$ band flux of the components at time $t$, and $\alpha$ and $\beta$ are coefficients which specify the relationship between the variation between the flux in $X$ and $V$ bands. As seen from the colour curves presented in earlier sections the values of $\alpha$ and $\beta$ lie in the range 1.20 to 0.80 for the spectral band range $U$ to $I$.

The quantities $A$ and $B$ can be evaluated if the difference in $V$ magnitudes between the components and the $B - V$ colour of the hotter component at the reference level are known. If we assume the difference in $V$ magnitudes between the components and the $B - V$ of the hotter component, from the
unspotted $B$ and $V$ magnitudes of the system, the values of $F_h^V$, $F_c^V$, $F_h^B$ and $F_c^B$ can be calculated. If suitable assumption of the values of $\alpha$ and $\beta$ are made, the quantities $A$ and $B$ can be calculated from each set of $B$ and $V$ observations and the individual $V$ and $B$ light curves of the two components can be computed.

Assuming that both components are light variables an attempt was made to separate the individual $V$ light curves of the components for possible ranges in their $V$ mag difference and $B - V$ colour of the hotter component. The possible range in the values of $\alpha$ and $\beta$ were also considered. It was found that for all the cases tried the resulting light curves of the two components show a large scatter ($> 0.2$ mag), indicating that the assumption that the cooler star also varies appreciably is not true. The large scatter results because neither $A$ nor $B$ thus derived represents the actual situation.

Table 10. Computed values of $\alpha$ in different spectral bands

<table>
<thead>
<tr>
<th>Spectral band</th>
<th>$T_\alpha = 4000$ K</th>
<th>$T_\alpha = 3500$ K</th>
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</thead>
<tbody>
<tr>
<td>$U$</td>
<td>$1.133\pm0.003$</td>
<td>$1.054\pm0.003$</td>
</tr>
<tr>
<td>$B$</td>
<td>$1.078\pm0.002$</td>
<td>$1.035\pm0.002$</td>
</tr>
<tr>
<td>$R$</td>
<td>$0.961\pm0.001$</td>
<td>$0.967\pm0.001$</td>
</tr>
<tr>
<td>$I$</td>
<td>$0.851\pm0.002$</td>
<td>$0.907\pm0.002$</td>
</tr>
</tbody>
</table>

The values of $\alpha$ in $UBRI$ bands computed for two spot temperatures $T_\alpha = 3500$ K and $T_\alpha = 4000$ K are given in Table 10. The photospheric temperature $T_p$ was assumed to be 5500 K, corresponding to the spectral type G2IV. The limb-darkening coefficients were the same as those listed in § 3.3. The light curves were generated in $UBVRI$ bands using the computer program described in § 3.3., assuming that the light variation is caused by a rectangular spot bounded by a latitudinal belt of $\pm20^\circ$. The spots were also assumed to extend over the entire range in longitude on the hemisphere visible at light minimum. The angle of inclination of the rotational axis was taken as $i = 50^\circ$, same as that suggested for HD 155555 by Pasquini et al.
(1991). The values of $\alpha$ listed in Table 10 were then derived assuming a linear relationship between the magnitudes in $UBRI$ bands and that in $V$ band.

If the cooler component is a non-variable then $B = 1.0$, and therefore

$$A = \frac{F_i^V - F_c^V}{F_h^V}$$

and the total flux observed in any other band $X$ is given by

$$F_i^X = F_h^X A^\alpha + F_c^X.$$ 

Assuming the values of $\alpha$, from the observed values $X_i$ the values of $F_h^X$ and $F_c^X$ can be computed if $A$ is known. The value of $A$ depends on the relative brightness of the two components. The various broadband colours of the two components derived from the data are plotted against the corresponding assumed difference in $V$ magnitudes of the two components in Figures 10 and 11. All the observations were treated with equal weights and the method of least square was used to derive the fluxes in the various spectral bands which in turn were converted to broadband colours.

Table 11. Computed colours of the hotter component for different spot temperatures

<table>
<thead>
<tr>
<th>Spot Temp.</th>
<th>$U - B$</th>
<th>$B - V$</th>
<th>$V - R$</th>
<th>$V - I$</th>
</tr>
</thead>
<tbody>
<tr>
<td>3500 K</td>
<td>0.12±0.02</td>
<td>0.68±0.01</td>
<td>0.38±0.01</td>
<td>0.60±0.01</td>
</tr>
<tr>
<td>4000 K</td>
<td>0.15±0.02</td>
<td>0.72±0.01</td>
<td>0.39±0.01</td>
<td>0.66±0.01</td>
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</table>

The colours derived for the hotter and the brighter component are nearly independent of the difference in brightness between the components at $V$ band. Table 11 gives the results for the hotter component for the two cases of spot temperature. The two sets of values mutually agree. They are well within the errors of their determination, indicating that the dependence of the derived colours on the values of $\alpha$ is rather weak. For the same value of
Fig. 10. Plots of broadband colours of the components against the assumed V mag difference between them
Fig. 11. Plots of broadband colours of the components against the assumed V mag difference between them.
The colours of the faint component derived depends appreciably on the $V$ mag difference between the two components that is assumed; they become redder as the cooler component becomes relatively fainter. The fraction $A$ in the reduction of $V$ band flux depends on the brightness difference between the components; the more the cooler star becomes fainter in $V$ the larger the value of $A$ since the observed variation directly gives variation in the hotter component. When the cooler star is relatively bright, the amplitude of light variation observed will be less than the actual amplitude.

The comparatively small errors in the derived colours given in Table 11 indicate that either the cooler star is a non-variable or the amplitude of light variation is insignificant; otherwise the assumption that $B = 1.0$ would have resulted in larger errors in the derived colours.

A limit on the brightness difference between the two components can be put if the cool component is a normal main sequence dwarf, i.e., if it does not exhibit an excess either in the red or ultraviolet. The values of $U - B$, $V - R$ and $V - I$ colours derived for the two components are plotted against corresponding $B - V$ colours in Figure 12 and 13. The mean colours of main sequence stars taken from Johnson (1966) are also plotted in the figures. The $V - R$ and $V - I$ in the Johnson’s system were converted to Cousin’s system using the calibration given by Fernie (1983). The error in the $U - B$ colour of the hotter star is $\sim 0.02$ mag and for all the other colours it is $\sim 0.01$ mag. The errors in $B - V$, $V - R$ and $V - I$ of the cooler component are less than 0.03 mag in the entire brightness difference range considered while that in $U - B$ colour increases rapidly as the cooler component becomes relatively fainter and fainter. Therefore in Figures 12 and 13 the upper limits (bluer) on the colours of the cooler star are plotted.

The $V - R$ colour of the hotter star lies exactly on the curve defined by the mean colours of main-sequence stars in both Figures 12 and 13 while the $U - B$ and $V - I$ colours lie about 0.1 mag above the respective curves. In the case of the cooler star also the $V - R$ curve lie very close to the same defined by the main sequence stars while the $V - I$ curve lies on an average about $0.10-0.15$ mag below that defined by the main-sequence stars. The near symmetric placing of the $V - I$ colours of the hotter and cooler
Fig. 12. Plots of $U-B$, $V-R$ and $V-I$ against the corresponding $B-V$ colour.
Fig. 13. Plots of $U - B$, $V - R$ and $V - I$ colours against the corresponding $B - V$ colour
star about the mean colours of the main-sequence stars in Figures 12 and 13 probably results from the assumed linear relationship between the amplitudes in V band I bands. The corresponding effects in B – V and V – R colours will not be appreciable because the difference in the corresponding effective wavelengths are smaller.

If the above argument is true the U – B of the cooler star should be only about 0.15-0.20 mag below the U – B curve defined by the main-sequence stars since the U – B of the hotter star is about 0.15 mag above it. This would be possible only if B – V of the cooler star is about 0.92-0.98. From Figures 10 and 11 it is found that the the active star should be brighter than the other by 0.8±0.2 mag when it is unspotted if its B – V should lie in the above range. The colours of the cooler component corresponding to this brightness difference are given in Table 12.

Table 12. Expected colours of the cooler component if it is about 0.8 mag fainter than the hotter.

<p>| | | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>U – B</td>
<td>B – V</td>
<td>V – R</td>
<td>V – I</td>
</tr>
<tr>
<td>0.90±0.10</td>
<td>0.95±0.05</td>
<td>0.56±</td>
<td>1.20±</td>
</tr>
</tbody>
</table>

According to the spectral type – mean colour relation given by Johnson (1966) the colours given in Tables 11 and 12 correspond to a spectral type slightly later than G5 for the hotter component and slightly earlier than K5 for the cooler component.

5.2.6. Amplitude and phase of light minimum

The values of \( V_{\text{max}} \) and \( V_{\text{min}} \) of HD 155555 given Table 9 are plotted against the mean epochs of observation in Figure 14a. The vertical bar gives the amplitude of light variation at that epoch. Both \( V_{\text{max}} \) and \( V_{\text{min}} \) show similar pattern in their long-term behaviour; both increased from 1979.70 onwards and attained their maximum values during 1984.30 and afterwards.
Fig. 14. (a) Plots of $V_{\text{max}}$ (open circles) and $V_{\text{min}}$ (filled circle) against the corresponding mean epoch. (b) plot of phase $\varphi_{\text{min}}$ against the mean epoch.
decreased. The trend continued till 1990.58 when the star was last observed. The maximum value of $V_{\text{max}} = 6.630$ mag that occurred during 1984.30 is probably close to the unspotted magnitude of the star. The maximum amplitude (0.135 mag) was observed during 1987.28 and 1989.61 and the minimum (0.05 mag) during 1990.58. Even though HD 155555 is observed at a fairly large inclination ($i > 50^\circ$, Pasquini et al. 1991) the amplitudes of light variation observed are relatively small (< 0.13 mag) when compared to that observed in RS CVn systems where amplitudes of the order of 0.20 to 0.30 mag are quite common. The smaller amplitudes most likely is due to the presence of active regions on both hemispheres because the amplitude depends only on the longitudinal asymmetry.

In Figure 14b we have plotted the observed $\phi_{\text{min}}$ listed in Table 9 against the corresponding mean epoch of observation. It appears from the figure that the phase of light minimum $\phi_{\text{min}}$ was within $0.2 - 0.4$ between 1979.70 and 1987.28 without any significant change. The light curve obtained during 1988.39 is nearly out of phase with that obtained one year earlier; the former curve is shown in Figure 7 and the latter in Figure 6. The sudden shift in the $\phi_{\text{min}}$ observed between 1987.28 and 1988.39 indicates that a new spot group had formed about an opposite longitude. The already existing spot group started decaying as indicated by the brightness at the corresponding photometric phase. The spots probably did not disappear completely since the $V_{\text{max}}$ observed during 1987.28 was less than the brightest magnitude observed. During 1989.16 one more spot group appeared at a different longitude, shifting the effective longitude of active regions to 0.35. The drop in $V_{\text{max}}$ and the fact that the brightness around 0.8 did not increase suggest that spot groups observed earlier were also present. The light curve obtained during 1990.58 shows that spots were nearly uniformly distributed over the entire longitude over the latitudinal belt that is involved in the rotational modulation because the amplitude of light modulation was only around 0.05 mag. The light minimum, as seen from Figure 8, is flat extending over more than 0.5; the corresponding $b - y$ colour does not show any modulation, but appears redder than that seen during the earlier occasions.