Spot activity in the RS CVn binary DM Ursae Majoris

M. J. Rosario, P. A. Heckert, M. V. Mekkaden and A. V. Raveendran

Vainu Bappu Observatory, Indian Institute of Astrophysics, Kavalur, Tamil Nadu, India
Western Carolina University, Cullowhee, NC 28723, USA
Indian Institute of Astrophysics, Bangalore 560034, India

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ABSTRACT
We present extensive UBVRI photometry of the active RS CVn binary DM UMa obtained at two different observatories over 1988–2008. We find the light curve of the star to be highly variable. The long-term photometry shows no evidence of any cyclic spot activity. On one occasion, the amplitude of modulation in V band was 0.30 mag, a rather high value for an active star in a binary seen at a comparatively low orbital inclination. The mean V magnitude of DM UMa during 1993–94 was brighter than that over 1979–85 by about 0.35 mag. We interpret the monotonic increase in mean brightness from 1984 onwards as due to the steady disappearance of star-spots in the near-polar latitudes of the star. The V-band data clearly show evidence for the presence of two distinct regions of enhanced spot activity on the visible primary, which are fixed in the orbital frame of reference, one facing the companion star and the other away from it. It appears that the nearby companion star suppresses the natural tendency of the active star for differential rotation and modifies the physical processes leading to the formation of spots, besides spinning it up by locking its rotation with the orbital motion. The variations in \((V - R)\) and \((V - I)\) colours with the V magnitudes clearly indicate that star-spots about 800 K cooler than the unspotted photosphere are responsible for the rotational modulation of light in DM UMa. The spot-filling factors derived from TiO-band strengths, which are available in the literature, are found to show the expected anticorrelation with the V magnitudes of the star. Apparently, there is excess flux in U and B bands, which increases as the star becomes fainter, partly compensating for the reduction of flux in those bands due to spot activity. The excess flux, probably, originates from plages or facular regions associated with the spot activity, and indicates that the simple two-component spot model with spotted and unspotted photospheric regions is not adequate to represent the star-spot activity in DM UMa.

Key words: stars: activity – binaries: spectroscopic – stars: individual: DM UMa – stars: late-type.

1 INTRODUCTION
DM UMa (BD+61°1211) belongs to the most active group of RS Canum Venaticorum binaries, which are presumed to undergo intense solar-type activity. It is the first RS CVn star to be classified by means of X-ray emission (Liller 1978; Charles, Walter & Bowyer 1979; Crampton, Dobias & Margon 1979; Schwartz et al. 1979). Though its light variability was established by Schwartz et al. (1979) from a study based on the Harvard archival plate collection, the first photoelectric light curve, which showed a large amplitude photometric wave that is characteristic of the RS CVn stars, was obtained by Kimble, Kahn & Bowyer (1981). DM UMa has since been the object of several photometric studies which showed that remarkable changes occur in the light curve of the star from season to season and even within the same season itself, indicating that large-scale variations occur in the surface distribution of star-spots on the active star on various time-scales (Mohin et al. 1985; Heckert et al. 1988; Heckert 1990; Mohin & Raveendran 1992, 1994).

Nations & Ramsey (1986) have reported that the strength of \(H\alpha\) emission in DM UMa varied by a factor of 3 over its orbital period during one of their observing runs. Significant changes in both the profile and equivalent width on time-scales as short as a few hours are found to occur in the spectrum of DM UMa (Tan & Liu 1985; Nations & Ramsey 1986). It is one of the four RS CVn binaries which are known to show \(H\alpha\) as pure emission feature above continuum at all times, the other binaries being V711 Tau, II Peg and UX Ari (Bopp 1983; Wacker et al. 1986).
DM UMa is a single-lined binary with a 7.5 d orbital period, and the active, visible component of the binary has been spectrally classified as K0–2 III–IV (Crampton et al. 1979; Kimble et al. 1981). The companion must be at least 1.5 mag fainter than the active primary because there is no visible trace of its presence in the spectrum of DM UMa (Crampton et al. 1979). The contribution to the total light from such a companion is expected to be negligible, and hence all the observed light variation can be ascribed to the active star of the binary system, making the interpretation of light variability less complicated.

Doppler images of star-spot distribution in RS CVn stars (Vogt et al. 1999) show long-lived polar spots, which have no solar analogue, on the active star. The orbital inclination of DM UMa is close to 40° (Kimble et al. 1981; Hatzes 1995), and hence a large circumpolar region will be presented to the observer. Any change in the spot distribution in the polar region will be reflected more on the mean brightness than on the amplitude of light modulation. The brightnesses at both the light curve maximum and minimum will be affected simultaneously by such changes. Therefore, reasonable guess on the distribution of spots in the polar region in DM UMa can be made at times from the light curves if we have long-term photometry.

The plots of \((B − V)\) colour against the corresponding \(V\) magnitude of active RS CVn stars, in general, show a large scatter, much larger than that expected from observational uncertainties (Ulvas & Henry 2005; Rosario, Raveendran & Mekkaden 2007). In the case of DM UMa, \((U − B)\) also shows a large scatter and at times it does not appear to follow the \(V\) and \((B − V)\) curves (Heckert et al. 1988; Heckert 1990). In analogy with the Sun, it is quite reasonable to expect the presence of bright facular or plage-like regions on the active star (Rodono & Cutispoto 1992; Tas, Evren & Ibanoglu 1999; Ulvas & Engvold 2003; Ulvas & Henry 2005). Such hotter regions, if present, would contribute more in the \(U\) spectral band than in the \(B\) band and almost negligibly in the \(I\) band, where only the effects of cool spots would be felt. Hence, long-term simultaneous multicolour photometry would be able to decouple the effects of bright facular regions and cool star-spots and provide convincing evidence for the presence of hotter regions along with the cool-star-spots on the stellar surface.

Extensive photometry of the active RS CVn binaries, UX Ari and V711 Tau, shows clear long-term modulations in \(V\) magnitude, indicating the possibility of spot activity cycles in these stars (Ulvas & Henry 2003; Lanza et al. 2006; Berdyugina & Henry 2007). Photometry obtained during 1979–91 shows that the mean brightness of DM UMa increased monotonically from around 1984 onwards while the amplitude of light variation remained within a narrow range of 0.16–0.23 mag without any apparent trend (Mohin & Raveendran 1994). The time baseline of the available data is not sufficient enough to give any information on any cyclic activity that may be operating in DM UMa.

Mohin & Raveendran (1994) have reported that the phase of light minimum observed during 1979–91 can be divided into four groups, with each group representing a short-lived spot group migrating towards decreasing orbital phases. This would imply that the latitude region, which is predominantly involved in producing the rotational modulation, is not synchronized with the orbital motion. The phase minimum actually indicates the effective longitude of spot distribution, and hence the formation of new spots and disintegration of old spots could produce an apparent migration of phase of light minimum (Mohin, Raveendran & Mekkaden 1995; Ulvas & Henry 2003). Long-term photometry would provide clear evidence of migration of spots on the stellar surface because the above short-scale migration would be superposed on the actual migration arising from the differential rotation, if any.

In order to clearly understand the spot activity in DM UMa, we have been monitoring it photometrically independently at Kavalur and Mt Laguna – at the former in \(BV\) bands since the discovery of its light variability in 1979 almost continuously except for a break during 1995–2003, and at the latter place continuously from 1986 onwards, initially for four years in \(UBV\) bands and later in \(UBVRI\) bands. The photometry obtained at Kavalur during 1980–91 and preliminary results of the observations at Mt Laguna during 1986–88 have already been published (Mohin et al. 1985; Heckert 1988; Heckert 1990; Mohin & Raveendran 1992, 1994). In this paper, we present the photometry obtained at Kavalur during 1993–2008 and that at Mt Laguna during 1988–2007. We also present an analysis of the long-term multiband photometry of DM UMa and discuss the implications of the results on the spot activity in the star.

### 2 OBSERVATIONS

During 1993–94 and 2004–08, DM UMa was observed on a total of 82 nights in standard Johnson \(BV\) bands with the 34-cm telescope of Vainu Bappu Observatory, Kavalur. All the measurements were made with respect to BD+60°1301 during 1993–94 and with respect to BD+61°1210 during 2004–08. BD+61°1210 and BD+60°1297 were observed as check stars during the first and second periods, respectively. In Table 1 (supplementary table; available only in the online version of the article), we have listed the differential \(V\) magnitude and \((B − V)\) colour of DM UMa with respect to BD+60°1301. The average differential magnitude and \((B − V)\) colour of the two comparison stars, in the sense BD+61°1210 minus BD+60°1301, \(ΔV = 0.466 ± 0.004\) and \(Δ(B − V) = 0.750 ± 0.003\), obtained at Kavalur over 1984–94, were used to convert the differential magnitude and colour of DM UMa with respect to BD+60°1301 to those with respect to BD+60°1301 before listing in the table. Each value given in the table is an average of three to four independent measurements. The typical uncertainties in \(ΔV\) and \(Δ(B − V)\) are 0.015 and 0.020 mag, respectively.

DM UMa was also observed with the 60-cm telescope operated by San Diego State University at Mt Laguna, CA, on a total of 213 nights simultaneously in standard Johnson \(UBV\) bands during 1988–89 and in \(UBVRI\) bands during 1990–2007. BD+60°1301 was used as the comparison and BD+60°1306 as the check star.

<table>
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<th>JD</th>
<th>(ΔV)</th>
<th>(Δ(B − V))</th>
<th>JD</th>
<th>(ΔV)</th>
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<td>49419.308</td>
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<td>–</td>
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<td>0.059</td>
<td>−0.175</td>
</tr>
</tbody>
</table>

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All the measurements were converted to differential magnitude and colours with respect to the comparison star and are given in Table 2 (supplementary table). Each value given in the table is an average of two independent measurements. The typical uncertainties in $\Delta V$, $\Delta (V - R)$ and $\Delta (V - I)$ are less than 0.010 mag and those in $\Delta (B - V)$ and $\Delta (U - B)$ are 0.015 and 0.02–0.04 mag, respectively.

In Tables 1 and 2, we have given the first two entries of the supplementary tables for illustrating their forms and contents.

3 ANALYSIS AND RESULTS

The present observations confirm the finding reported by Heckert et al. (1988) and Mohin & Raveendran (1994) that the light curve of DM UMa is highly variable. Even within a season the light curve, sometimes, showed appreciable changes. The light curves were always found to be highly asymmetric. Even though there were indications of a second minimum in the light curves of a few seasons, only that obtained during the 1993 season showed two fairly well defined minima. A few typical light curves, which clearly demonstrate the drastic variability in light curves exhibited by DM UMa, are given in Fig. 1; the Julian day interval and mean epoch of observations are indicated in the corresponding panel of the figure. In addition to the data given in Tables 1 and 2 (supplementary tables), all the $BV$ data of DM UMa available in the literature (Kimble et al. 1981; Mohin et al. 1985; Mohin & Raveendran 1992, 1994) were included in the present analysis. The Julian days of observation were converted to photometric phases using the ephemeris, $JD = 244\,7627.13 + 7.4949dE$.

The initial epoch corresponds to the conjunction with the visible primary in front, and the period is the orbital period. The period and the time of conjunction with the visible primary behind the secondary from which the above initial epoch was derived are from Strassmeier et al. (1993). The time of conjunction given in Strassmeier et al. (1993) is consistent with the time of maximum of radial velocity variation reported by Crampton et al. (1979). An uncertainty of 0.0001 d in the orbital period would cause an uncertainty of only around 0.02 p in the phase accumulated over 30 yr.

3.1 Long-term spot activity

We have plotted the differential $V$ magnitudes of DM UMa listed in the Tables 1 and 2 (supplementary tables) along with those available in the literature against the corresponding Julian days of observation in the top panel of Fig. 2. As seen in the figure, the star has been observed almost in every season since the discovery of its light variability in 1979 by Kimble et al. (1981), thus providing an uninterrupted baseline of 30 yr to look for any spot activity cycles similar to those seen in other active RS CVn binaries. The mean brightness of V711 Tau and UX Ari, which are two well-studied active RS CVn systems, shows cyclic variations with periods around 15 and 25 yr (Ulvas & Henry 2003; Berdyugina & Henry 2007). It is clear from Fig. 2 that DM UMa shows no such cyclic variation in mean brightness; if there is any cyclic variation, its period must be much larger than 30 yr. In this respect, DM UMa is similar to the single-lined RS CVn binary with a 12.7-d orbital period, IL Hya (Mekkaden & Raveendran 1998). The mean $\Delta V$ of DM UMa, which was on an average 0.50 mag during 1979–85, monotonically decreased to about 0.15 mag by 1993–94 and has remained more or less at the same level.

The fractional loss of light integrated over a photometric cycle is a good indicator of the total fractional area covered by the spots;
the integration ensures that proper weight is given to the asymmetry in the longitudinal distribution of spots. The value of $\Delta V = 0.02$ mag observed during the 2008 season is the brightest differential $V$ magnitude of DM UMa observed so far. Assuming $\Delta V = 0.0$ mag as the reference level, we have calculated the light loss over a photometric cycle by integrating the light curve formed from observations of each season, except those of 1982 which were divided into two to form two light curves, and the results are plotted in the middle panel of Fig. 2 against the corresponding mean epoch of observation. If the reference level chosen represented the actual brightness of the unspotted, quiescent photosphere, the values we derive would correspond to the actual fractional loss of light, and hence, the total fractional area covered by the spots over the stellar surface, if limb-darkening effects are neglected, during the corresponding epoch. A higher value for the unspotted brightness would increase the fractional loss of light computed at all epochs by the same amount without affecting the general trend in the variation.

From a modelling of the light curves, Lanza et al. (2006) have found that the total spot area on the active star of V711 Tau system varied cyclically with a period of $19.5 \pm 2.0$ years upon which low-amplitude modulations with periods in the range 3–5 yr were superposed. It is clear from Fig. 2 that DM UMa does not exhibit any such cyclic variation in the total spot area given by the fractional light loss over a photometric cycle. In fact, the spot area has monotonically decreased from 1979 onwards till present, but for two instants, one around 1983–84 and the other around 2002–03, when the spot area increased slightly. The increase in spot area during the first instant was rather abrupt. The figure shows that the rate of decrease before and after this was nearly the same, indicating that the formation of new spots that caused the sudden increase in the fractional light loss did not affect the ongoing decay of old spots considerably. This view is supported by the fact that the shape, amplitude and phases of maximum and minimum of the light curves of epochs 1983.35 and 1984.37 (Mohin et al. 1985) were quite similar.

All the differential $(B - V)$ values of DM UMa available are plotted in the bottom panel of Fig. 2 against the corresponding Julian days of observation. It is interesting to note that the long-term variations seen in the mean $\Delta V$ and fractional light loss are not reflected in the mean $(B - V)$ colour of the star. The $(B - V)$ colour, however, shows shorter time-scale variations on which the rotational modulation is superposed.

### 3.2 Phases of light minimum

The phases of minimum ($\phi_{\text{min}}$) of the light curves of DM UMa observed during the various seasons are plotted in Fig. 3 against the corresponding mean epochs of observation. Because of the broad minimum exhibited by the light curves at certain epochs, the uncertainty in some of the estimated $\phi_{\text{min}}$ is as large as $\pm 0.1$ p. The figure shows that the $\phi_{\text{min}}$ observed during 1979–2008 falls into two bands centred around 0.0 p and 0.5 p, apparently, without any systematic, long-term migration with respect to the orbital phase. The $\phi_{\text{min}}$ rather makes random excursions over a short range of orbital phases about its mean value.

The $\Delta V = 0.02$ mag at the light curve maximum observed during the 2008 season is the brightest differential $V$ magnitude of the star so far observed. Therefore, it is evident that throughout the period of observations, the cool spots, which are presumed to produce the observed light variation, never disappeared from the field of view over a rotational cycle, implying that the spots were spread over more than 180° in longitude over the stellar surface. The $\phi_{\text{min}}$ actually represents the centroid of the longitudinal distribution of spots, and hence any change in the surface distribution will be reflected in its value. The observations show that a change in $\phi_{\text{min}}$ is always accompanied by a change in the shape and amplitude of the light modulation, clearly indicating a corresponding change in the surface distribution of star-spots. Probably, several spots are involved.

![Figure 2](https://academic.oup.com/mnras/article-abstract/394/2/872/1071554)

**Figure 2.** Plots of differential $V$ magnitude of DM UMa (top panel), fractional light loss over its rotational period (middle panel) and differential $(B - V)$ colour against the corresponding Julian day of observation.

![Figure 3](https://academic.oup.com/mnras/article-abstract/394/2/872/1071554)

**Figure 3.** Plot of phase of minimum of the light curve ($\phi_{\text{min}}$) against the corresponding mean epoch of observation. The horizontal lines represent the mean of each group of $\phi_{\text{min}}$. 

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in the light modulation and the formation of new spots and decay of old spots occur over time-scales comparable to a few rotational cycles. The abrupt shifts in $\varphi_{\text{min}}$ or apparent migrations towards both decreasing and increasing orbital phases for short durations, at certain epochs, most likely, result from small-scale readjustments in the spot distribution and not from an actual migration as a result of a difference in the orbital and rotational periods (Mohin et al. 1995; Ulvas & Henry 2003). The large changes in the rate of migration, when $\varphi_{\text{min}}$ apparently shows a migration, also point to continuous changes occurring in the spot distribution over the stellar surface.

An RS CVn binary which is very similar to DM UMa, as far as the behaviour of $\varphi_{\text{min}}$ is concerned, is IL Hya. Mekkaden & Raveendran (1998) have reported that in that object a systematic migration of $\varphi_{\text{min}}$ is absent and the values of $\varphi_{\text{min}}$ are distributed about phases 0.0 and 0.5. In contrast to DM UMa, IL Hya quite often shows two well-defined minima in its light curve.

### 3.3 Colour variation and spot temperature

In Fig. 4, we have plotted the $\Delta V$, $\Delta(U - B)$, $\Delta(B - V)$, $\Delta(V - R)$ and $\Delta(V - I)$ obtained at Mt Laguna when the light modulation had the largest amplitude during the time-span covered by the present observations. The amplitudes of variation in $\Delta V$ and $\Delta(B - V)$ were 0.30 and 0.04 mag, respectively. These values are almost the same as those observed by Kimble et al. (1981) in 1979. The amplitude of $(V - I)$ variation was 0.08 mag while $(U - B)$ and $(V - R)$ colours had amplitudes of 0.05 and 0.03 mag. It is clear from the figure that the star becomes redder as it becomes fainter, which is consistent with the general understanding that star-spots cooler than the ambient photosphere are causing the modulation of observed light in RS CVn binaries.

![Figure 4](https://academic.oup.com/mnras/article-abstract/394/2/872/1071554)

**Figure 4.** Plots of $V$ magnitudes and various colours of DM UMa obtained at Mt Laguna in 2000 against the corresponding photometric phases computed using the ephemeris JD $= 244 7627.13 + 7.4949$ d E.

Of all the $V$-band light curves obtained by us, the one shown in the figure has the least asymmetry. It is nearly sinusoidal and resembles closely that obtained by Kimble et al. (1981). A large amplitude means a large difference in spot coverages in the latitude belts on the hemispheres seen at light maximum and minimum, which mainly contribute to the light modulation.

The various differential colours obtained at Mt Laguna over 1988–2007 are plotted in Fig. 5 against the corresponding differential $V$ magnitude. The data obtained in 2000 and plotted in Fig. 1 are indicated by a separate symbol. We find from the figure that the $(V - R)$ and $(V - I)$ colours are well correlated with the corresponding $\Delta V$ indicating tight relationships between them. Remarkably, the colours obtained in 2000 follow the same relationships defined by the observations obtained over the other 16 seasons. The scatter about the mean in both cases is nearly the same as the errors in their measurements. Both $(B - V)$ and $(U - B)$ colours, although consistent with the star becoming redder at fainter visual magnitudes, show a scatter about their respective mean variations, which is significantly larger than their respective uncertainties. The scatter in $(U - B)$ colour is more prominent than...
that in \((B - V)\). We did not include the \((B - V)\) observations of DM UMa obtained at Kavalur in the plot so as to avoid additional scatter arising from the slightly higher observational error and any possible slight systematic differences between the two photometric systems arising from the use of different comparison stars. The \((B - V)\) and \((U - B)\) colours observed in 2000, although show the same trends in their mean variations with \(\Delta V\) as shown by the respective colours obtained during the other seasons, lie systematically below them, contrary to what is shown by the \((V - R)\) and \((V - I)\) colours.

The \(\Delta(U - B)\), \(\Delta(B - V)\) and \(\Delta(V - R)\) colours of DM UMa obtained at Mt Laguna are plotted against the corresponding \(\Delta(V - I)\) colours in Fig. 6. The colours obtained in 2000, again, are indicated by a separate symbol. The figure shows that there is a well-defined relationship between \((V - R)\) and \((V - I)\) colours, as expected from what is seen in Fig. 5; again, the scatter about the mean is consistent with the errors in their measurements. Though \((B - V)\) and \((U - B)\) colours also show the same trend with a variation in \((V - I)\) colour as that shown by the \((V - R)\) colour, the spread about the mean is appreciably larger than that expected from observational errors alone. The spread in \(\Delta(U - B)\) colour is more prominent than that in \(\Delta(B - V)\).

Assuming an unspotted photospheric temperature of 4500 K for DM UMa (Hatzes 1995; O’Neal et al. 2004), we have computed the expected variations in all the colours for a range of spot temperatures. For each spot temperature, the projected area of spots over the visible hemisphere was varied, and the net expected \(V\) magnitude and the various colours were computed. Both the photosphere and spots were assumed to radiate as blackbodies and the effective wavelengths of observation in \(UBVRI\) bands were taken as 0.36, 0.44, 0.55, 0.70 and 0.90 \(\mu m\). We have assumed \(\Delta V = 0.0\) mag to represent the unspotted photospheric brightness; this is about 0.02 mag brighter than the brightest magnitude of the star so far observed. In Figs 5 and 6, the results of computation are presented for three different spot temperatures, 3300, 3700 and 4000 K. It is clear that a spot temperature of about 3700 K fairly satisfies the observations in \(VRI\) bands simultaneously. The extrapolated values of \(\Delta(V - R) = 0.051\) and \(\Delta(V - I) = 0.065\) at \(\Delta V = 0.0\) mag were used to normalize the computed values before plotting in the figures. We assumed \(\Delta(B - V) = -0.160\) and \(\Delta(U - B) = -0.480\) at \(\Delta V = 0.0\) mag for DM UMa so that the computed curves for the spot temperature of 3700 K, which satisfies the variations in \(VRI\) magnitudes, approximated the \(\Delta(U - B)\) and \(\Delta(B - V)\) colours obtained at Mt Laguna in 2000.

The main drawback of the procedure adopted for the derivation of the spot temperature is that the effects of differential limb darkening are neglected in the computations. Using synthetic light curves, Mekkaden & Raveendran (1998) have shown that the net effects in colours produced by limb darkening depend on the exact distribution of spots on the stellar surface, and that the effects could be even negligible for spot distributions with large longitudinal extents. They find that even for a circular spot seen centrally at low minimum, the limb-darkening effects are almost negligible for a large fraction of the light curve. The effect of differential limb darkening is to make the colours redder than what they would be in the absence of any limb darkening. Since the limb-darkening coefficients monotonically increase towards shorter wavelengths (Strassmeier, Hall & Henry 1994), the differential effects would make the \((V - I)\) colour more red than the \((V - R)\) colour. From Fig. 5, we find that if that is the case the \((V - I)\) variation would indicate a temperature higher than that indicated by the \((V - R)\) colour. But, the figure clearly shows that a spot temperature of about 3700 K fairly represents the variations in both \((V - I)\) and \((V - R)\) colours with the \(V\) magnitude of the star. Probably, the effects of limb darkening in the differential \(UBVRI\) magnitudes observed are less than the corresponding observational errors because of the prevalent surface distribution of spots.

O’Neal, Neff & Saar (1998) and O’Neal et al. (2004) have determined star-spot temperature in DM UMa by fitting the TiO 7055 Å and 8660 Å bands in its spectra; they used the spectra of normal inactive K and M giants to represent the spectra of unspotted and spotted photospheric regions. Assuming an unspotted photospheric temperature of 4500 K, they have derived a temperature of 3570 ± 100 K from two spectra obtained in 1995 and 3450 ± 126 K from six spectra obtained in 1998. The mean spot temperature derived by us from the long-term \(VR\) photometry is in close agreement with this value which validates the assumption that the effects of limb darkening in various photometric bands are less than the respective observational errors.

### 3.4 Latitudinal extent of spot distribution

Computations show that if spots of 1000 K cooler than an unspotted photosphere of temperature 4500 K are restricted to within ±40° about the equator, as in the case of the Sun, a 100 per cent coverage over the entire visible longitude range would cause an amplitude of only about 0.55 mag in \(V\) band. The maximum amplitude of \(V\)-band modulation shown by DM UMa is 0.30–0.32 mag. This would require about 60–65 per cent spot coverage over the ±40° latitude belt. Additionally, the opposite hemisphere should be completely devoid of any spots. For a smaller fraction of spot coverage, the
latitude of spot formation should be substantially above 40°. From Fig. 2, we see that the total range in V magnitude of DM UMa, the difference in the magnitudes at the brightest light maximum and faintest light minimum, is 0.60. Assuming that the brightest magnitude corresponds to the unspotted photosphere, even for a 100 per cent spot coverage it is essential that star-spots form well beyond 40° in latitude. A higher brightness for the unspotted photosphere would correspondingly increase the upper latitude limit of spot formation.

The light curves obtained during 244 7157–8037 (1988.2–1990.4), when the mean light level of DM UMa increased and its fractional light loss decreased at a steady rate (Fig. 2), are presented in Fig. 7. The shape of the light curve did not change appreciably over the period; there were only minor changes. The phases at both the light curve maximum and minimum migrated towards decreasing orbital phases by about 0.1 p. The most remarkable aspect of the changes in the light curve is the overall steady increase in the brightness with time; the increases in brightnesses at light curve maximum and minimum were similar. If spots are predominantly restricted to within ±40°, in a manner similar to but not exactly like, about the equator, the observed change in the light curve would require a uniform reduction in the spot area across the entire stellar longitudes; an amplitude of 0.32 mag in V band observed in 1979 completely rules out such a possibility. The most likely explanation for the observed behaviour is that in DM UMa spots were present over a substantial area at latitudes much higher than 40° and because of the comparatively low orbital inclination these spots were always presented to the observer. The rapid and steady increase in the mean brightness resulted from a reduction in the spot area at these latitudes. These spots were not exactly polar spots, otherwise we would not have observed a slow decrease in the amplitude of light modulation as the spot area decreased from 1984 onwards. Similarly, a comparison of light curves obtained in 1983 and 1984 (Mohin et al. 1985) shows that the sudden increase in the fractional light loss during 1983–84 resulted from the formation of spots at very high latitudes in the circumpolar region.

Large-scale spot activity in the near-polar region is probably not a very common feature in DM UMa since for almost 20 yr starting from about 1990 the brightnesses at light maximum and minimum simultaneously did not change appreciably indicating that new spots did not form on a large scale. Another point worth noting about the spot activity in near-polar latitudes in DM UMa is the rather slow decay of the spots in that region. The observations of DM UMa were begun when it was already undergoing the decay of very high latitude spots.

4 DISCUSSION

We discuss below some of the implications of the results of our analysis on the spot activity in DM UMa.

Since the orbital inclination of DM UMa is close to 40° (Kimble et al. 1981; Hatzes 1995), the parallel to 40° latitude in one hemisphere will be crossing the disc centre, and the major contributions to the light modulation will come from star-spots in the 0°–60° latitude region. Assuming that the spots form symmetrically about the equator, the absence of any systematic migration of φmin implies that at least the region within ±60° of the equator rotates almost synchronously with the orbital motion. The effective longitudes of spot distribution, therefore, are fixed in the orbital frame of reference. From Fig. 3, it may be noted that φmin more often occurs around 0.5 p than around 0.0 p. The zero-point of phase corresponds to the conjunction with the visible primary in front, and hence at 0.5 p of the light curve the hemisphere facing the companion will also be facing the observer. Rosario, Mekkaden & Raveendran (2008) find clear evidence for longitudinal asymmetry in the spot activity, which is fixed in the orbital frame of reference, in the active RS CVn system UX Ari with the hemisphere facing the companion more active. They have suggested that the differential rotation is almost absent in the active star of the UX Ari binary system and that the presence of the companion significantly affects the physical processes that produce the spots on the active star.

The 1998 photometric observations of DM UMa at Mt Laguna was started 52 days after the end of the spectroscopic run by O’Neal et al. (2004). The spot-filling factor fS, which is the same as the total projected area of star-spots on the visible hemisphere, determined by them from the absolute strengths of TiO bands, is plotted along with the differential V magnitudes in the middle panel of Fig. 1. The amplitude of light modulation in V band in 1998 was only 0.1 mag, and over the phase range 0.8–1.5 the V magnitude varied by only 0.04 mag. Five out of the six spectroscopic observations fall within this range of photometric phases. Despite these and an uncertainty of about ±0.05 in the values of fS, we can make out from the figure that DM UMa shows the expected anticorrelation between fS and V magnitude. A comparison of the observations obtained in 1997 and 1998 shows that during the intervening period of 50 d between the spectroscopic and photometric observing runs, most likely, there were no major changes in the V light curve. According to the top panel of Fig. 5, the range of 0.13–0.23 in ΔV corresponds to a projected fractional spot area in the range 0.16–0.26 for a spot temperature of 3700 K. The spot-filling factors derived by O’Neal et al. (2004) lie between 0.28 ± 0.06 and 0.42 ± 0.06. So there is a possibility that the unspotted brightness could be about 0.15 mag brighter than the assumed value of ΔV = 0.0 mag in the computation.

The only Doppler image of surface distribution of spots on DM UMa that is available is the one presented by Hatzes (1995). As is typical of what has been seen in the active components of RS CVn binaries, the mean image derived by simultaneously fitting the CaI

Figure 7. V-band light curves of DM UMa during the period of steady increase in its mean brightness. The photometric phases are computed using the ephemeris JD = 244 7627.13 + 7.4949 d E. Note the small reduction in the amplitude of light variation as the mean brightness of the star steadily increased over the time-span.

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photometry is essentially because of the observed in 1979 and 2000. During both the occasions, the amplitude of the emission and He(I) ranges 0.62–0.32 and 0.36–0.137 mag, respectively. The mean ΔV observed in 1979 was actually bluer by about 0.04 mag relative to that observed in 2000. The mean (B − V) colours of DM UMa in 1979 and 2000 differ by 0.32, with the star fainter on the former occasion. We would expect the (B − V) observed in 1979 to be correspondingly redder by about 0.04 mag relative to that observed in 2000. The mean Δ(B − V) observed in 1979 and 2000 are −0.137 ± 0.012 and −0.137 ± 0.011, respectively. Both DM UMa and the comparison star used have almost the same (B − V) colour, and hence, the systematic errors arising from any differences in the respective photometric systems will be negligible. We assert that the (B − V) colour of DM UMa in 1979 was actually bluer by about 0.04 mag than that expected from the extrapolation of its (B − V) colours observed in 2000 to fainter V magnitudes. Since the variations in VRI magnitudes are consistent with star-spots of a temperature around 3700 K, this would imply that the increased spot activity did not produce a proportionate reduction in the B-band flux. Or, equivalently, there was an excess B-band flux in 1979 that slightly offset the reduction due to the increased spot activity. It appears that the scatter seen in the plot of Δ(B − V) against ΔV, unlike in the case of Δ(V − R) and Δ(V − I) against ΔV, partly arises from the changes in the excess B-band flux at different epochs.

We have plotted in Fig. 9 the Δ(U − B) and Δ(V − I) colours of DM UMa obtained at Mt Laguna against the corresponding...
and the (B − V) magnitudes indicate the definite presence of high temperature regions in the form of plages or faculae associated with the cool spots.

The phases of minimum of light curve in DM UMa are distributed in two bands centred around two effective longitudes, one facing the companion and the other away from it. The phase of light minimum represents the centroid of longitudinal distribution of spots, and hence the small-scale changes in the phase minimum indicate the small-scale changes in the longitudinal distribution of spots on the stellar surface. The presence of effective longitudes, which are fixed in the orbital frame of reference, implies that at least the region ±60° about the equator rotates in near synchronism with the orbital motion. Since a large latitudinal spread is implied we may conclude that the differential rotation is either absent, or negligibly small in DM UMa. In such a case, it is evident that the presence of the companion helps in not only spinning up the active star but also in suppressing its natural tendency for differential rotation and modifying the processes that produce spot activity on the active star. Even though there are uncertainties in the procedures resulting in inconsistent conclusions regarding differential rotation (Vogt et al. 1999; Petit et al. 2004), only Doppler imaging can provide a definite answer on the lack of any differential rotation in active stars of RS CVn binaries.

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SUPPORTING INFORMATION

Additional Supporting Information may be found in the online version of this article:
Table 1. Sample of the table of BV photometry of DM UMa obtained at Kavalur.
Table 2. Sample of the table of UBV RI photometry of DM UMa obtained at Mt Laguna.

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