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Photometric study of the RS CVn binary DM Ursa Majoris

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Abstract. Differential BV photometry of DM UMa obtained on 77 nights during the six observing seasons over the years 1984–90 is presented. The phases of the light minima observed during 1988–90 are found to be nearly the same. The variation in $B-V$ indicates that the star is redder at fainter visual magnitudes. We have analyzed all the B and V light curves of DM UMa available from 1979 onwards by means of a spot model which assumes that large discrete spots are responsible for the observed light variation; the method of least squares was employed to derive the best-fit spot parameters. Observationally, we find that from 1984 onwards the brightness at light curve maximum has increased monotonically (by $\sim$0.20 mag), whereas the amplitude of light variation has remained within a narrow range (0.16–0.23 mag) without any apparent trend; the modelling indicates a slow migration of the spots towards the equator, and a gradual decrease of the spot area during the corresponding period. We derive a mean spot temperature of 3400 ± 60 K from the data obtained during ten of the observing seasons.

Key words: photometry – spectroscopic binary – DM UMa – late-type – variable

1. Introduction

The RS Canum Venaticorum binary DM UMa (= BD +61°1211 = SAO 015338) is one of the most active members of its class, and has been the object of several observational studies at wide wavelength regions (Schwartz et al. 1979; Charles et al. 1979; Crampton et al. 1979; Kimble et al. 1981; Mohin et al. 1985; Nations & Ramsey 1986; Heckert 1990). It is a single-lined spectroscopic binary with an orbital period of 7.492 d, and the spectral type of the visible component is K0–K1 III–IV (Crampton et al. 1979; Kimble et al. 1981). Like other members of its class, DM UMa displays strong and variable Ca II H and K emissions in its spectra (Charles et al. 1979). It is one of the few RS CVn systems (others include V711 Tau, UX Ari, and II Peg) which show Hα in emission above continuum at all times (Bopp 1982), and Nations & Ramsey (1986) have reported variability in Hα on time-scales as short as a few hours.

The most prominent and striking photometric characteristic of RS CVn stars in general is the wave seen in their light curves; these waves often change in shape, mean light level, and amplitude. Extensive photometry by Mohin et al. (1985) has indicated that the light curves of DM UMa obtained during any two seasons do not agree in shape, amplitude, phases of light maximum and minimum, and mean light level. In order to evolve a comprehensive model that would accommodate all the various observed properties, the nature of variations and the various time-scales involved should be known in sufficient detail; this calls for more frequent and systematic observations. To account for the unusual photometric behavior of the RS CVn objects, various models have been proposed, and the explanation in terms of surface activity, in the form of spots, has received the strongest support from wide band photometry.

DM UMa was observed as part of a photometric program on RS CVn systems and related objects, and in this paper we present its BV photometry obtained during the years 1985–90. We also present and discuss the results of an analysis of its B and V light curves available from 1979 onwards till the present on the assumption that large discrete starspots are responsible for the observed light variation; the method of least squares was used to derive best-fit values of the spot parameters.

2. Observations

DM UMa was observed on a total of 77 nights during the six observing seasons, 1984–85 (11 nights), 1985–86 (4 nights), 1986–87 (30 nights), 1987–88 (13 nights), 1988–89 (7 nights), and 1989–90 (12 nights) with the 34-cm reflector of Vainu Bappu Observatory, Kavalur, using standard B and V filters. The comparison stars were BD +60°1301 and BD +61°1210. All the observations were made differentially with respect to BD +60°1301 and transformed to the UBV system. The mean differential magnitudes and colours of the comparison stars, in the sense, BD +60°1301 minus BD +61°1210, obtained during five of the seasons are given in Table 1 along with the corresponding number of observations (n); the values are consistent and indicate their nonvariability. Table 2 gives the results for the variable star, in the sense, DM UMa minus BD +60°1301. Each value given in Table 2 is a mean of three to four independent measurements; the typical error in ΔV is ±0.010 mag and in $\Delta(B-V)$ is ±0.014 mag.

In Fig. 1 we have plotted the values of $\Delta(B-V)$ against the corresponding values of ΔV given in Table 2. Most likely, $(B-V)$ is correlated with V, in the sense that the star is redder at fainter visual magnitudes. A reduction of 42% occurs in χ^2 if we assume

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Table 1. The mean differential magnitudes and colours of comparison stars, in the sense, BD +60°1301 minus BD +61°1210

Season	ΔV	n	$\Delta(B-V)$	n
1984–85	-0.462 ± 0.007	11	$+0.751 \pm 0.004$	9
1986–87	-0.470 ± 0.002	22	$+0.745 \pm 0.003$	13
1987–88	-0.450 ± 0.002	5	$+0.742 \pm 0.007$	5
1988–89	-0.465 ± 0.003	7	$+0.757 \pm 0.004$	7
1989–90	-0.464 ± 0.003	10	$+0.747 \pm 0.004$	10

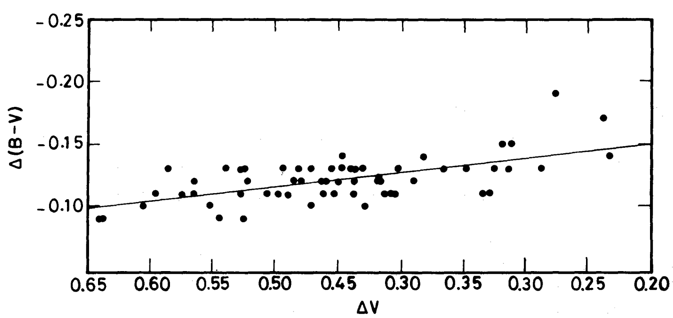


Fig. 1. Plot of $\Delta(B-V)$ against the corresponding ΔV given in Table 1

a linear relationship between V and $B-V$ instead of the assumption that $(B-V)$ fluctuates about a mean value independent of V. The slope of the assumed linear relationship derived using the least-square technique is 0.125 ± 0.014, which is consistent with that reported by Mohin et al. (1985).

3. Discussion

It has been fairly well-recognized that the peculiarities exhibited by RS CVn objects in wide wavelength regions from radio to X-ray, when compared to single stars of similar spectral types, can be understood in terms of enhanced solar-type activities. The photometric variations seen in these objects have been attributed to the rotational modulation of light by the cool spots, analogues to sunspots, present on the active component of the system. Basically, there are two different approaches that have been followed to reproduce the light curves using starspot models: (i) a continuous distribution of small spots within an equatorial belt (Eaton & Hall 1979; Kimble et al. 1981), and (ii) a small number of large discrete, usually one or two, spots, in most cases at high latitudes (Dorren & Guinan 1982; Poe & Eaton 1985; Rodono et al. 1986; Zeilik et al. 1990). There is no solar analogue for the high-latitude spots; however, at the same time, at present there are no compelling reasons from theoretical considerations that rule out their occurrence either. The simple solutions of Doppler imaging techniques using high-resolution spectra suggest a small number of large spots, sometimes even close to the poles (Rodono et al. 1986). Another indirect evidence suggesting the presence of large discrete spots comes from the recent detection of a localized magnetic field in the RS CVn binary HR 1099 by Donati et al. (1990). It is true that the above suggestions are based on models, and to arrive at a unique solution is rather difficult because of the inverse nature of the problem which involves several parameters; perhaps, modelling the observations, both spectroscopic and photometric, obtained during several seasons might give important clues on the nature of starspots.

Table 2. The differential magnitudes and colours of DM UMa

JD (Hel.) 2440000.+	ΔV	$\Delta(B-V)$	JD (Hel.) 2440000.+	ΔV	$\Delta(B-V)$
6055.4601	0.635	−0.098	6056.4580	0.640	−0.093
6084.3898	0.540	—	6086.4002	0.579	—
6088.3666	0.439	−0.134	6090.3591	0.485	−0.120
6095.3834	0.459	−0.127	6118.2387	0.455	−0.136
6120.2888	0.497	−0.110	6120.3939	0.493	−0.130
6121.2346	0.526	−0.138	6122.3535	0.552	−0.118
6123.2669	0.585	−0.132	6471.4080	0.583	—
6473.3927	0.565	—	6505.3019	0.449	—
6506.3071	0.443	—	6817.4329	0.424	—
6819.3579	0.381	−0.140	6820.3401	0.415	−0.125
6821.3202	0.468	—	6825.3777	0.417	−0.121
6825.4813	0.403	−0.137	6828.3195	0.457	—
6828.3288	0.456	—	6828.3425	0.470	—
6828.3580	0.453	—	6829.3517	0.543	—
6830.3098	0.521	—	6830.3462	0.522	−0.125
6830.3694	0.539	−0.131	6831.3714	0.458	—
6832.3246	0.446	−0.133	6833.4003	0.409	—
6834.2975	0.396	—	6835.3052	0.420	—
6836.2854	0.504	—	6846.2664	0.466	—
6847.2806	0.428	−0.105	6850.3460	0.407	−0.118
6851.2975	0.471	−0.104	6852.2884	0.527	−0.114
6853.3386	0.479	−0.126	6857.3351	0.395	—
6858.2536	0.450	−0.121	6859.3459	0.524	−0.136
6860.2573	0.506	−0.110	6861.2438	0.463	−0.120
6862.2502	0.436	−0.131	6877.2767	0.436	—
6883.1848	0.481	—	6884.2116	0.471	−0.138
6892.2755	0.430	—	7157.4257	0.452	—
7178.3509	0.574	—	7179.3813	0.489	—
7183.3386	0.437	—	7184.3705	0.524	−0.099
7185.4286	0.564	−0.128	7198.3102	0.461	—
7200.3523	0.566	—	7201.3099	0.544	−0.091
7230.2368	0.605	−0.102	7232.3000	0.430	−0.131
7233.2821	0.412	—	7238.2963	0.595	—
7556.4260	0.311	−0.155	7557.3616	0.324	−0.130
7558.4298	0.404	−0.113	7559.3064	0.437	−0.126
7560.3367	0.481	−0.135	7561.3781	0.418	−0.126
7572.4274	0.334	−0.119	7852.4624	0.446	−0.149
7853.4286	0.364	−0.132	7855.4626	0.270	—
7856.4210	0.313	−0.130	7869.4159	0.275	−0.197
7912.3177	0.389	−0.127	7913.3303	0.329	−0.119
7915.3238	0.232	−0.149	7916.4041	0.287	−0.138
7917.3413	0.318	−0.157	7918.3846	0.347	−0.131
7922.3211	0.237	−0.178			

The brightness at light curve maximum has been found to vary in almost all well-observed RS CVn systems. On the basis of the starspot model, this can be accounted for by either of the two likely phenomena occurring on the surface of the active star: (i) changes in the longitudinal distribution of spots present in the equatorial region, and (ii) changes in the area of spots present in the polar region. Specifically, in the case of DM UMa, the brightness at light maximum observed in 1984 is fainter by ~0.20 mag than that observed during 1989–90. Assuming that the light maximum observed on the latter occasion corresponds to the unspotted star, the change in the brightness at light maximum observed on the former occasion can be accounted for on the assumption of four nearly equal equatorial spots at longitudes separated by ~90°. If the spots are cooler by ~1300 K than the undisturbed photosphere they should cover a total fractional area of ~0.28 (assuming orbital inclination $i=40°$). The total fractional area within a belt of $\pm 30°$ about the equator is 0.50, and hence there will be no room left to accommodate the spots needed for the light modulation in addition to the change in the brightness at light maximum if spots are restricted only to the equatorial region. It is to be noted that a change of ~0.20 mag in the light maximum can be produced by a single spot covering a fractional area ~0.07, if situated at a higher latitude.

In light curve modelling, usually, the spot parameters are derived by varying the different parameters systematically until acceptable approximation to the observations is obtained, and in almost all cases the temperatures of the spots were fixed initially, and only a single wavelength band data were made use of (Rodono et al. 1986, and references therein; Budding & Zeilik 1987; Zeilik et al. 1988). Poe & Eaton (1985) have derived starspot areas and temperatures in several binary systems with late-type components; they first determined the best-fit latitude, longitude, and size for the spots that reproduce the shape and amplitude of the V curve, and then used the amplitude of a colour curve, usually $(V-I)$, to define the spot temperature. In the case of BH Vir, a short period RS CVn binary, Zeilik et al. (1990) have determined the spot temperature using multiband photometry; they used the V band data to determine the size of the spot (assuming $T=0$ K) and then adjusted the ratio of the flux of the spot to that of the photosphere at I band to derive the spot temperature (similarly, they have compared the B and R band observations also).

The present approach considers the method of least squares to arrive simultaneously at the best-fit values for the various parameters, including the temperature, assuming that the light variation is caused by a limited number of discrete large spots. The presence of a strict minimum in the sum of the squares of the deviations in the multidimensional parameter space is indicated by the absolute convergence of the solution on iteration; the problem of choosing the final parameters from a set of possible values does not arise in this method because all the spot parameters are optimized simultaneously instead of optimizing each one of them independently. Apart from avoiding any personal bias thus, this method also allows the simultaneous determination of the spot temperature when observations are available in more than one wavelength band. In this respect the present method is different from the other spot modelling methods existing in the literature. In the following we outline the method of analysis and the results of application of the method to the BV photometric data of DM UMa available over years 1979–90.

3.1. Method of analysis

We make the following assumptions: (i) the spotted star is spherical, (ii) both the undisturbed and spotted regions radiate like black bodies, and (iii) limb-darkenings in the two regions follow quadratic laws. The monochromatic luminosity of the undisturbed star is then given by,

$$L_\lambda = R^2 B_\lambda(T_*) \int \{1 - A_*(1-\cos\theta) - B_*(1-\cos\theta)^2\} \cos\theta \, \mathrm{d}A,$$

where R is the stellar radius, T_* is the effective temperature, $B_\lambda(T_*)$ is the Planck function, A_* and B_* are the limb-darkening coefficients, dA is an element of surface area, and θ is the angle between the line of sight and the radius along dA; the integration is over the visible hemisphere. The change in luminosity due to the presence of a spot of effective temperature T_s is given by,

$$\Delta L_\lambda = R^2 B_\lambda(T_*) \int \{1 - A_*(1-\cos\theta) - B_*(1-\cos\theta)^2\} \cos\theta \, \mathrm{d}A$$
$$- R^2 B_\lambda(T_s) \int \{1 - A_s(1-\cos\theta) - B_s(1-\cos\theta)^2\} \cos\theta \, \mathrm{d}A,$$

where A_s and B_s are the limb-darkening coefficients of the spotted region, and the integrations are over the visible spot area. If several discrete spots are present, the total change in luminosity is obtained using,

$$\Delta L_\lambda^{\mathrm{T}} = \sum_{\mathrm{spots}} \Delta L_\lambda.$$

The magnitude of the star at photometric phase ϕ is given by

$$m_\lambda(\phi) = -2.5 \log \frac{L_\lambda - \Delta L_\lambda^{\mathrm{T}}(\phi)}{L_\lambda} + M_\lambda, \tag{1}$$

where M_λ is the unspotted magnitude of the star. In the case of light contribution by a nearby companion, L_λ in Eq. (1) should be replaced by $L_\lambda(1+R_\lambda)$, R_λ being the luminosity ratio of the components at λ.

The above considerations are general to the extent that no assumptions are made either on the specific shape of the spots, or on their nature, whether cool or hot. For the present analysis we assumed that the spots are circular in shape, and hence the four parameters, spot radius (θ_{R}), polar distance (θ_{P}), longitude (θ_{L}) and temperature (T_s) describe a spot completely. The assumptions are simplistic. The fact that there is always a clear rotational modulation, in most cases with one or two well-defined minima, indicates that most of the light variation is due to a prominent spot group. There may be additional spots or spot groups scattered over the surface contributing negligibly to the overall light modulation. An irregular spot, or spot group can be replaced by an "equivalent" circular spot, and the spot parameters thus determined would refer to this equivalent spot. Under such an approximation, modelling a single light curve would not be of much significance; but modelling a series of light curves obtained during several successive seasons would be helpful in investigating the average spot characteristics and spot evolution. Spot parameters can also be obtained spectroscopically using the techniques of Doppler imaging (Vogt & Penrod 1983). But in systems like DM UMa, where the rotational velocities are low, this technique would be very difficult. The observed magnitude is a function of $\Delta L_\lambda^{\mathrm{T}}$ which in turn is a function of the above parameters of the various spots. If we denote these by θ_1, θ_2, etc., Eq. (1) can be written in the functional form as

$$m_\lambda = m_\lambda(\phi, \theta_1, \theta_2, \ldots). \quad (2)$$

For a least-square solution of the spot parameters, we follow the method outlined in Scarborough (1964) for a nonlinear function. Expanding Eq. (2) about the initial guess values for the spot parameters θ'_1, θ'_2, etc., using Taylor's theorem,

$$m_\lambda = m_\lambda(\phi, \theta'_1, \theta'_2, \ldots) + \left(\frac{\partial m_\lambda}{\partial \theta_1}\right)_0 \delta\theta_1 + \left(\frac{\partial m_\lambda}{\partial \theta_2}\right)_0 \delta\theta_2 + \ldots$$

The derivatives $(\partial m/\partial \theta_1)_0$, $(\partial m/\partial \theta_2)_0$, etc., are obtained at $\theta_1 = \theta'_1$, $\theta_2 = \theta'_2$, etc. The above equation is linear in $\delta\theta_1$, $\delta\theta_2$, etc., and using the observational data normal equations (equations of condition to minimize the sum of the squares of residuals) can be formed in the usual way, and any standard technique can be used to solve them. Here $\delta\theta_1$, $\delta\theta_2$, etc., are the corrections to the initial guess values, and the procedure is repeated by replacing θ'_1, θ'_2, etc., by $\theta'_1 + \delta\theta_1$, $\theta'_2 + \delta\theta_2$, etc., until convergence is reached. The various derivatives are evaluated numerically using

$$\left(\frac{\partial m_\lambda}{\partial \theta_1}\right)_0 = \frac{m_\lambda(\phi, \theta'_1 + \Delta\theta_1, \theta'_2, \ldots) - m_\lambda(\phi, \theta'_1 - \Delta\theta_1, \theta'_2, \ldots)}{2\Delta\theta_1},$$

$$\left(\frac{\partial m_\lambda}{\partial \theta_2}\right)_0 = \frac{m_\lambda(\phi, \theta'_1, \theta'_2 + \Delta\theta_2, \ldots) - m_\lambda(\phi, \theta'_1, \theta'_2 - \Delta\theta_2, \ldots)}{2\Delta\theta_2},$$

etc.

The monochromatic luminosities at the effective wavelengths of observation were evaluated numerically by taking about 200 surface area elements, and a similar number of area elements were taken inside the region of a spot to compute ΔL_λ. On doubling these numbers the changes in the net magnitude is found to be less than $1.0\,10^{-4}$. To compute the derivatives we used a value of 2° for $\Delta\theta_R$, $\Delta\theta_P$ and $\Delta\theta_L$, and a value of 20 K for ΔT. The resulting normal equations were solved using the Cracovian matrix method given in Kopal (1959), since along with the coefficients it gives the uncertainties involved in their evaluation. The derivatives can also be derived using these uncertainties for $\Delta\theta_R$, $\Delta\theta_P$, etc., after the first iteration, but we found no additional advantage; the convergence is reached faster, but the computation time increases since after each iteration the standard deviation of fit has to be calculated for the evaluation of the uncertainties.

The computer program in Fortran developed by us is fairly general; there is no restriction either on the number of discrete spots, or on their latitudes or longitudes; the temperature of the spots may be treated as either known, or unknown, in which case it may be either the same for all the spots or different for different spots. The determinacy of the spot parameters is indicated by their absolute convergence on iteration from the starting initial guess values; otherwise divergence occurs with the spot area or temperature finally becoming negative. Our trials with synthetic data indicate that the choice of the initial guess values are not critical for achieving the convergence of the solution.

3.2. Results of analysis

In the case of DM UMa, the observations of Kimble et al. (1981) show an orbital modulation of $(B-V)$ with an amplitude of about 0.04 mag. Because of the low amplitudes (<0.20 mag against the 0.32 mag in V band observed by Kimble et al. 1981) and slightly larger error our data do not show up the $(B-V)$ variation as strikingly as the data of Kimble et al. do. In Fig. 2, we have plotted the V and B light curves due to a circular spot of radius $\theta_R = 31.5°$ at a polar distance of $\theta_P = 11.5°$ (typical values derived for DM UMa, Table 3) for a few selected spot temperatures. The orbital inclination was taken as $i = 40°$, and the limb-darkening coefficients in V and B were taken as $A = 0.78$ and $A = 0.92$, respectively; the photospheric temperature was taken as $T_* = 4700$ K. The calculations show that the amplitude of light variation in V band is 0.14 mag and the corresponding amplitude of $(B-V)$ modulation is around 0.026 mag due to a spot of temperature $T_S = 3400$ K. Out of this the contribution due to the differential limb-darkening (estimated using the case $T_S = 0$ K) is 0.018 mag, indicating that any determination of temperature separately from the amplitude of $(B-V)$ modulation is meaningless. Poe & Eaton (1985) have clearly demonstrated that the wavelength dependence of limb-darkening contributes a large fraction of the variation in the colours $(U-B)$, $(B-V)$, and even $(V-R)$, and they have suggested that only the $(V-I)$ colour curve can be used as a reliable indicator of spot temperature.

We find from Fig. 2 that the shape of the light curve does not change substantially with change in temperature (the shape depends mainly on the spread of the spotted region); however the mean light level changes appreciably with the spot temperature.

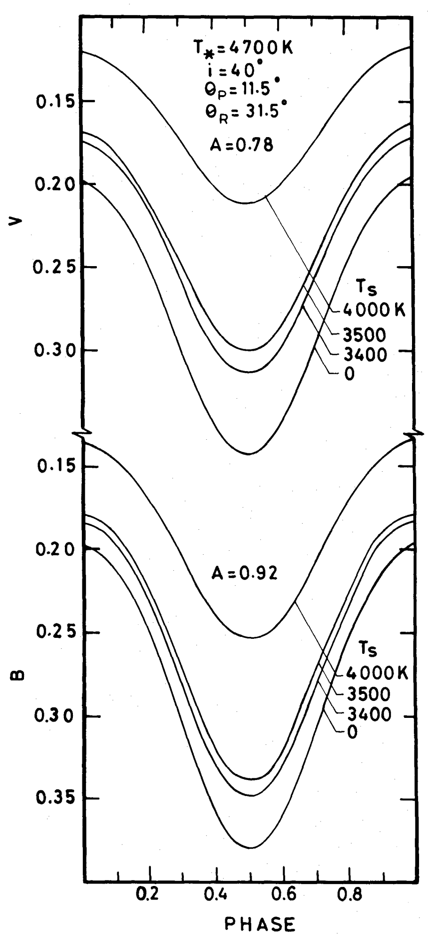


Fig. 2. V and B light curves for different assumed spot temperatures. The spot parameters are indicated in the figure. The unspotted V and B magnitudes are taken as 0.0 mag

Table 3. The spot parameters derived for the light curves of DM UMa

Mean epoch	Polar distance (degrees)	Longitude (degrees)	Radius (degrees)	Temperature (K)	Fractional area	S.D. of fit (mag)	No. of obs.		Ref.
							V	B	
1979.42	24.6±0.7	177±1	32.0±0.6	3230±190	0.076±0.003	0.023	21	21	1
1980.17	13.8±0.6	160±2	32.7±0.7	3190±200	0.079±0.003	0.027	32	21	2
1981.22	71.8±8.5	71±1	31.7±2.0	3560±90	0.075±0.009	0.013	30	17	2
	25.2±4.6	265±3	25.8±1.0	3560±90	0.050±0.004				
1982.21	2.0±1.2	172±39	27.9±0.3	3400 (assumed)	0.058±0.001	0.035	33	—	2
1983.35	27.0±1.8	123±3	27.0±0.3	3400 (assumed)	0.054±0.001	0.020	8	6	2
1984.37	12.6±0.4	93±1	34.1±0.3	2800±240	0.086±0.001	0.018	24	22	2
1985.06	8.7±0.6	55±4	34.1±0.9	3380±190	0.086±0.005	0.019	11	9	3
1986.46	11.0±0.6	226±3	36.4±1.5	3640±160	0.098±0.008	0.022	11	11	4
1987.10	11.5±0.4	207±2	31.9±0.8	3610±100	0.075±0.004	0.016	36	18	3
1988.07	17.9±1.1	0±3	32.7±1.4	3490±210	0.079±0.007	0.022	13	5	3
1989.02	19.9±1.4	3±3	28.1±2.3	3720±250	0.059±0.009	0.015	7	7	3
1990.09	32.7±3.3	348±5	21.9±2.8	3400±920	0.036±0.009	0.035	12	11	3

References: (1) Kimble et al. (1981); (2) Mohin et al. (1985); (3) Present study; (4) Heckert et al. (1988)

The changes in the amplitudes of the light curves are much larger than the change in the amplitude of the colour curve. From the figure we also find that larger changes occur in V band than in B band indicating that observations at longer wavelength bands are more suitable for the determination of the spot parameters, especially the spot temperature.

In the bottom panel of Fig. 3, we have plotted the expected amplitudes of modulations of $(B-V)$, $(V-R)$, and $(V-I)$ colours. The limb-darkening coefficients in R and I bands were taken as $A=0.57$ and $A=0.45$, respectively (Poe & Eaton 1985). From the figure we find that largest modulations in colours are produced by spots of temperature ~ 3500 K on a photosphere of temperature 4700 K. The differential limb-darkening contributes a large fraction of the variation in all the colours including $(V-I)$. The effects due to temperature in $(B-V)$ and $(V-R)$ colours are nearly the same (<0.01 mag), indicating that $(V-R)$ observations do not have any appreciable advantage over $(B-V)$ observations (see also the top panel of Fig. 3); but in the $(V-I)$ colour, the effect due to the temperature is larger (~ 0.02) making it the more suitable for the determination of spot temperature. It is clear from the figure that even an uncertainty of ~ 0.01 mag in the determination of colour amplitude would lead to a rather large uncertainty (>500 K) in the determination of spot temperature, if spot temperature is determined separately from the colour modulation.

In the top panel of Fig. 3 we have plotted the various colours and the brightnesses in BVRI bands at the light minimum (the unspotted magnitudes were assumed to be zero at all bands). It is clear that a substantial fraction of the changes in colours results from the differential limb-darkening and the change in brightness at light minimum is appreciably large at all bands for spot temperatures larger than 3000 K. For spots cooler than 3000 K the changes in V and B magnitudes are less.

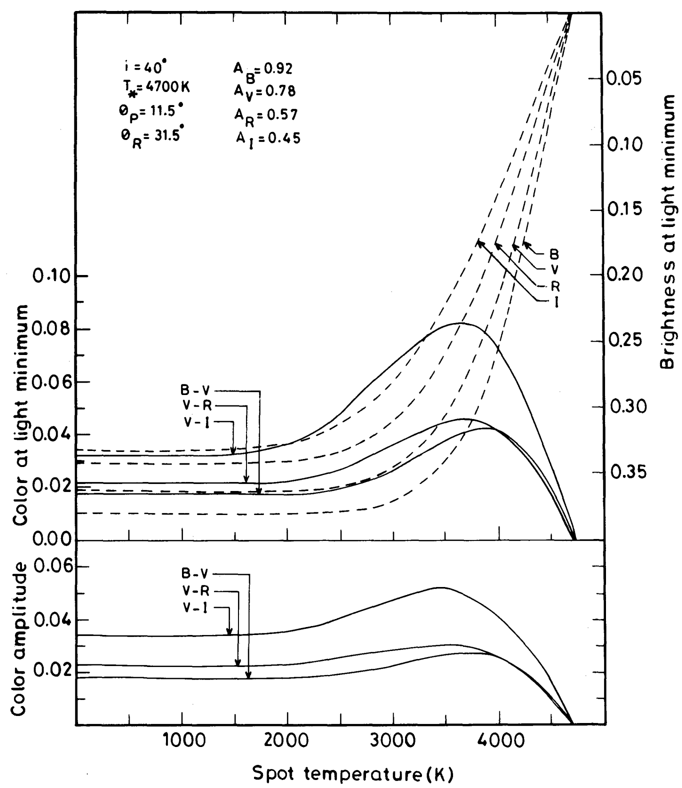
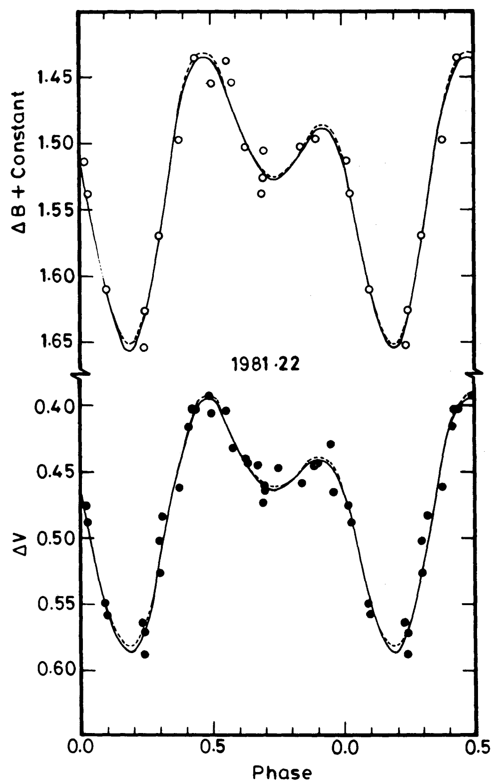
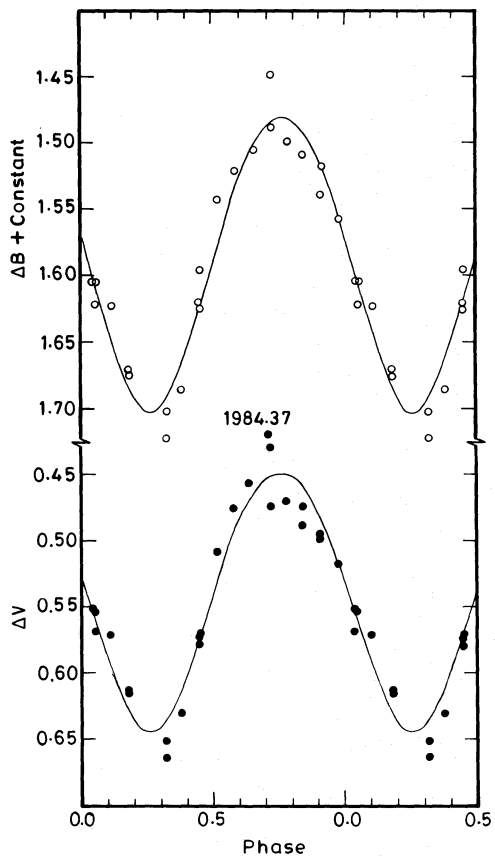


Fig. 3. Top panel shows the variation in various colours and brightnesses at light minimum in BVRI bands. The expected amplitudes of various colour modulations with spot temperature are shown in the bottom panel. The unspotted magnitudes in all bands are assumed to be 0.0 mag

In the present case the B and V observations were directly and simultaneously used instead of using the amplitudes of the V and $(B-V)$ modulations separately, and the spot temperature was treated as an unknown in the least-square solution along with the other spot parameters. Both B and V observations were given equal weights in the solution of spot parameters. The temperature determination relies upon the overall fit of both V and B light curves, and hence on the information contained in the entire light curve. The program was tested with synthetic BV data, and we could retrieve the input spot temperature along with the other spot parameters.

We could not determine the V magnitude of the comparison star precisely; however, our measurements yield a mean $B-V = 1.183 \pm 0.013$ for it. To convert the differential magnitude and colour of the variable to V and B magnitudes that are needed for the analysis, for the comparison star we assumed $V = 0.0$ mag. With this, for the variable ΔV becomes V, and $[\Delta(B-V)+\Delta V + 1.183]$ becomes B; the ordinates in Figs. 4a–c are these values. As mentioned earlier, DM UMa is a non-eclipsing binary, and hence the orbital inclination is unknown. An uncertainty in the inclination will be reflected directly on the polar distance of the





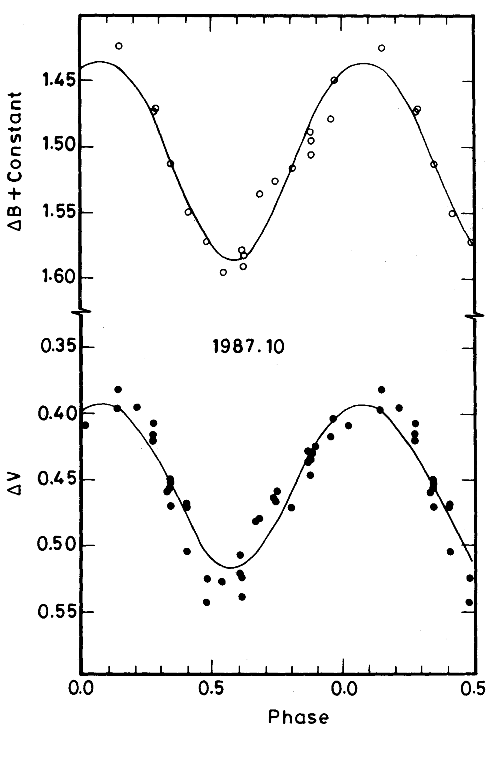


Fig. 4a–c. Plots of observations in B and V bands (open and filled circles, respectively) along with the corresponding best fit computed curves. The epoch of observations is given in the corresponding figure. In Fig. 4a, the results for the same set of spot parameters for quadratic limb-darkening laws for the spotted and unspotted regions are also shown as dashed curves

spot. For the present analysis we used $i=40°$, the probable value suggested by the mass function and the luminosity ratio (Crampton et al. 1979; Kimble et al. 1981). The other parameter that is uncertain and the assumed value of which has a similar direct effect on the polar distance in models that allow high-latitude spots is the magnitude of the unspotted star. The problems associated with the assumption of the unspotted magnitudes have already been discussed in detail by Poe & Eaton (1985). If the actual unspotted magnitude is higher than that assumed in the treatment of the model then the derived spot area and temperature would be of differential in nature. Our calculations show that an increase of unspotted brightness by ~ 0.1 mag would decrease the spot temperature by ~ 200 K. DM UMa has been observed every year since the discovery of its light variation in 1979 by Kimble et al. (1981), and the value $\Delta V = 0.23$ mag with respect to the comparison star BD $+60°1301$, observed by us during 1989–90, is the brightest magnitude observed so far. We assumed this to represent the V magnitude of unspotted star, and the corresponding $B=1.26$ mag to represent the unspotted B magnitude. The assumed unspotted magnitudes seem to be not very far from the truth because the spot temperatures derived for DM UMa (Table 3) are consistent with that derived for starspots in other similar systems by Poe & Eaton (1985). The effective temperature of the undisturbed photosphere was taken as $T_* = 4700$ K, which according to Johnson (1966) approximately corresponds to the above-mentioned spectral type and the assumed unspotted $B-V=1.03$ mag. The nature of the secondary component of DM UMa is unknown; it is probably a late-type dwarf (Kimble et al. 1981), and we neglected the contribution of the secondary in the B and V spectral regions.

In addition to the observations given in Table 2, the BV photometry given by Kimble et al. (1981), Mohin et al. (1985), and Heckert et al. (1988) were also subjected to the above described method of analysis. The Julian days of observation were converted into orbital phases using the following ephemeris (Crampton et al. 1979):

$$\mathrm{JD(Hel.)} = 2443881.4 + 7\overset{d}{.}492E,$$

where the initial epoch corresponds to the time of maximum of positive radial velocity, and the period is the orbital period mentioned above. To illustrate the spot modelling we have shown in Figs. 4a–c the available B and V band observations along with the computed B and V light curves (plotted as open and filled circles) obtained in a few cases. Table 3 summarizes the results of the least-square analysis; it gives the mean epoch of observation, the polar distance, longitude and temperature of spots, area of spots as a fraction of the total surface area of the star, the standard deviation of fit, the number of observations in V and B bands, and the reference from where the data were taken. In two cases, namely, observations with mean epochs 1982.21 and 1983.35, the temperature of the spots were assumed (mean of the temperatures derived in other cases) because in the first case only V band data are available, and in the second case the data available for analysis are few in number. It is found that a high latitude single spot could reproduce all the light curves except that obtained during early 1981 where two spots are found to be necessary to account for the light variation. In all the cases considered the standard deviation of the fit $\sigma = \sqrt{(O-C)/(n-L)}$ (where n is the total number of observations in B and V bands and L is the total number of parameters solved for) is found to be of the order of the scatter seen in the data, which is largely due to the temporal changes that occur in the light curves within a few orbital cycles, probably as a result of changes in the configuration of spots. The present model assumes that the spots are circular in shape, i.e. a spot or spot group of irregular shape (which is more likely) is effectively replaced by an "equivalent" spot of circular shape. This assumption seems to account for all the light variation seen; the slightly larger standard deviation of fit obtained in some cases may be probably due to the departure from this approximation.

Calculations were made with the same linear limb-darkening law for both the spots and undisturbed photospheric region. The linear coefficients used, $A=0.78$ for the V band and $A=0.92$ for the B band, were derived from interpolations of the values tabulated by Manduca et al. (1977) for the solar composition. The above authors have reported that their computations indicate that the darkening is remarkably insensitive to surface gravity in B and V bands. In Fig. 4a the computed curves with different quadratic limb-darkening laws for the spotted and unspotted regions and for the same set of spot parameters are also shown ($A_*=0.77$, $B_*=0.01$, $A_s=1.08$, and $B_s=-0.24$ for the V band, and $A_*=1.07$, $B_*=-0.22$, $A_s=1.36$, and $B_s=-0.50$ for the B band; these values correspond to temperatures $T_*=4700$ K, $T_s=3500$ K, $\log g=1.5$, and $[A/H]=0.0$, and were derived from the tables of Manduca et al. 1977). It is clear that the differences between the two cases of limb-darkening are insignificant, well within the observational uncertainties; the least-square solutions show only marginal differences in the resulting spot parameters and negligible difference in the standard deviations of fit to the data.

Out of the 12 observing seasons considered, we could derive spot temperatures for the data obtained on 10 occasions; this is the first time such an attempt has been made from an extensive set of data for an RS CVn object. From Table 3, it is seen that the derived spot temperatures lie in the range 2800 ± 240 K to 3720 ± 250 K, with a mean of 3400 ± 60 K. In view of the uncertainties in the determination, it is difficult to be sure whether the differences in the temperatures seen at different epochs are real. The derived temperature represents the effective temperature of the equivalent large spot. Hence, a difference in the effective spot temperatures observed at different times probably indicates various distributions of spot sizes and temperature at different epochs.

In Fig. 5, we have plotted the observed quantities, amplitude of light variation and brightness at light curve maximum, and the derived spot parameters, fractional area, polar distance and longitude. The set of observations with the mean epoch 1982.21 shows a larger scatter and does not define the light curve well, and the least-square solution indicates a single large polar spot; because of the large errors involved, in Fig. 5 we have not plotted the corresponding longitude and polar distance.

From Fig. 5 we find that from 1984 onwards the brightness at light curve maximum has increased nearly monotonically (by ~ 0.2 mag), whereas the amplitude has remained within a narrow range (0.16–0.23 mag) with no apparent trend. Qualitatively, this implies a disappearance of high-latitude spots and a corresponding reduction in the spot area.

The results of modelling indicate the presence of spots at high latitudes at all times; only in one case there is an indication of an additional low-latitude spot (mean epoch 1981.22, $\theta_P = 71°$; incidentally, the spot area was the highest during this epoch). From a study of light curves of several objects using spot modelling, Rodono et al. (1986) and Zeilik et al. (1990) have already noted

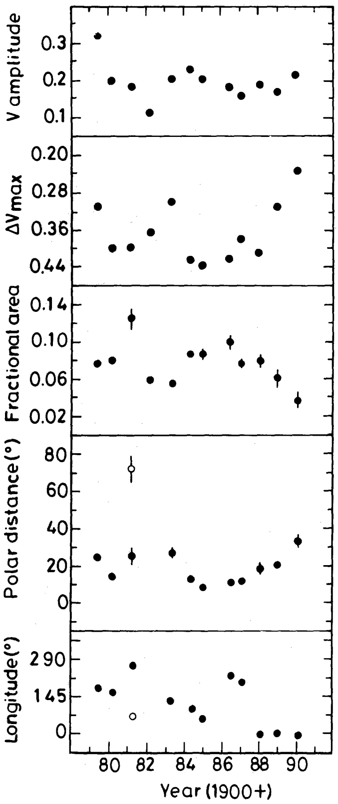


Fig. 5. Plots of the observed quantities, the amplitude of light variation, the brightness at light curve maximum, and the derived spot parameters, fractional area, polar distance and longitude, against the corresponding epoch of observations. Open circles represent the low-latitude spot

that high-latitude spots seem to be commonplace in active spotted stars. We find from Fig. 5 that the high-latitude spots can be traced (as indicated by closely lying θ_P and θ_L values, probably, with a slight migration) for two or three consecutive seasons, whereas there is no trace of the low-latitude spot during the earlier or later seasons (since no spot was seen close to its θ_P and θ_L immediately before or after); this implies, probably, a lower life-time for the "center of activity" if present near the equator when compared to, if present at higher latitudes. During the period 1988–90, the longitudes of the spots have remained close to $\sim 0°$, but the latitudes have drifted slightly towards the equator. We also find from Fig. 5 that there is a slow migration of spots in latitude towards the equator from 1984 onwards, and a decrease in the spot area during the same period; this result is contrary to what is observed in the Sun.

Further systematic and more frequent observations with a larger wavelength baseline (suitably in V and I bands) and over much extended time interval are required to investigate the spot parameters in a consistent manner and to check the possibilities discussed above.

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