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By

Padmakar
S. K. Pandey

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New BVR photometry of six prominent RS CVn binaries.

Padmakar and S.K. Pandey*

School of Studies in Physics, Pt. Ravishankar Shukla, University, Raipur, 492 010, India.

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Abstract. A new BVR photometry of six prominent RS CVn stars: V711 Tau, UX Ari, IM Peg, II Peg, σ Gem and λ And, carried out during 1995-97, is presented. The new results reveal significant evolution in the shape as well as in the amplitude of light curves of these binaries. The traditional two-starspot model has been used to obtain the spot parameters from the observed light curves of the stars. Changes in spot area and their location on stellar surface can be noticed from extracted spot parameters. Some of these stars are found to have significant variation in (B-V) and (V-R) color indices. The (V-R) colour index variation found in IM Peg, II Peg and λ And have been used for determining starspot effective temperatures.

Key words: Stars-variables: stars-binaries: stars-activity: stars-chromosphere: starspots

1. Introduction

During the past two decades considerable attention has been focussed on RS CVn binaries and other chromospherically active stars. In order to investigate the physical characteristics of starspots, evolution of spotted regions as well as overall long-term cyclic variation, it is essential to perform systematic monitoring of active stars for long time spans. The photometric monitoring of the stars using small telescopes is economic and relatively easy to perform, therefore, it can provide an effective means of tracing out the evolution of starspots of the chromospherically active stars. Keeping this objective in mind we have started a systematic observing programme on RS CVn binaries, using the 0.35m Celestron Schimdt-Cassegrain telescope at the University Observatory. In this paper we present new differential BVR photometry of six prominent, non-eclipsing RS CVn binary stars. The new data will be useful for studying the long-term behaviour of starspots.

Send offprint requests to: S.K. Pandey
* *Senior Associate of IUCAA, Pune, India*

2. Observations

The BVR photoelectric photometric observations of the six RS CVn stars were carried out during the period November, 1995 to February, 1997, using the 0.35m Schmidt-Cassegrain telescope (C-14) equipped with SSP-5A photoelectric photometer and Johnson standard broad band filters. The detector used in SSP-5A photometer is R4457 photomultiplier tube (PMT). The response curves of the B and V filter and R4457 PMT detector system closely match those of Johnson standard B and V response functions, respectively, whereas our R passband is close to the Rc in the Cousins system. For each variable star, a star as close as possible to the program star, having colour and magnitude similar to the program star, and used by previous observers were chosen as comparison stars. The details of variable and comparison stars are given in Table 1. Observations were corrected for the atmospheric extinction and transformed into the standard photometric system. Each data point isan average of four to five independent observations. The uncertainty in ΔV, Δ(B-V) and Δ(V-R) are 0.012, 0.015 and 0.013 mag, respectively.

3. Starspot Modeling

The photometric variation attributed to starspots can provide useful informations about physical characteristics (size, location, effective temperature etc.) of the spotted stars. Over the past few years, several attempts have been made to treat light curve of spotted stars with one or two-spot models (Bopp & Evans 1973; Budding 1977; Dorren 1987; Strassmeier 1988; Eker 1994; Henry et al. 1995; Kővári & Bartus 1997 and references therein). In order to account for long term variation analogous to sunspot cycle a time dependent formulation of the spot model has been introduced by Strassmeier & Bopp (1992), and later on used by others (Strassmeier, Hall and Henry 1994; Oláh et al. 1997). A new approach, considering multiple random spots, has recently been introduced by Eaton et al. (1996) to solve the erratic behaviour of light variation in active stars. To evaluate geometric parameters of starspots from observed light curves we have used our computer program based on the analytical formulation for the circular starspots given by Dorren (1987). For each star we have extracted the value of the maximum brightness ever observed from the literature (see Table 1). These values were further used as the unspotted light level of each star.

Polar spots as well as the spots uniformly distributed in longitudinal belts do not produce any rot ational signature in the light output, and hence are indistinguishable as far as light modeling is concerned. In order to reproduce the light curve of a given star in the framework of a spot model either polar spots or spots distributed uniformly in a longitudinal belt are used to produce changes in the light level of photometric variation. The photometric spot modeling, Doppler imaging(Hatzes & Vogt 1992; Strassmeier et al. 1991) as well as theoretical models (Solanki et al. 1997) seem to support the existence of spots at high latitudes and/or polar spots in chromospherically active stars. Therefore, we have chosen one of the spots permanently located at the pole. To model the V as well as the colour light curves spot parameters, namely, the longitude (λ), latitude (β), radius (γ) and (ΔT) were taken as free parameters and rest of the parameters *i.e.* inclination (i), limb darkening co-efficient (u) etc. were kept constant.

We have adopted constant ΔT to evaluate flux ratio between the spot and photosphere using a simple black body approximation with $\Delta T \sim 1000$ K for the stars showing insignificant colour variations. For the stars (IM Peg, II Peg and λ And) having significant colour variation we have adopted the procedure of modeling (V-R) colour indices curve to extract ΔT and area as described by Poe & Eaton (1985). Using Dorren's (1987) spot model with three spots having one always at the pole, observed light curves were fitted and the best fit parameters (λ, β, γ, ΔT) of the two spots plus the size of the polar spot were evaluated by simultaneously using gradient and grid search least square fitting method (Bevington 1969). We have also tested the modeling technique for various noise levels to check the reliability and stability of the results. To trace out absolute minima in χ^2-parametric space we iterated the fitting procedure with different initial values of parameters, and the solutions with overlapping spots were discarded. The final best fit parameterg with their uncertainties are listed in Table 2.

4. Results and Discussion

The new multi-colour photometric observations reported here not only reflect the present status of activity ofn these stars, but it also would prove to be very useful for future long-term photometric study. Our observations cover the entire phase of light variations of these stars and this would be quite useful for starspot modeling and other spot activity diagnostics.

4.1. V711 Tau

The variability of non-eclipsing double-lined spectroscopic binary V711 Tau is being continuously monitored photometrically as well as spectroscopically since its discovery as a variable star by Landis & Hall (1976). Recent papers containing extensive photometric analysis of this star are by Mohin & Raveendran (1993a) and Henry et al. (1995). The knowledge of the orbital inclination is very important for the latitude determination of starspots, and this parameter($i = 30°$) has been obtained with high accuracy by Fekel (1983) and Donati et al. (1990). In the past, several attempts have been made to fit photometric light curve of this star in terms of large dark spots (Dorren et al. 1981; Kang & Wilson 1989; Henry et al. 1995 and references therein). Here, BVR photometry of V711 Tau obtained during 1996-97 for total 42 nights is presented. A remarkable variation in the light curve within a year can be seen from Fig.1. Differential amplitude jumps from 0.07 to 0.18 mag, whereas minima still persist at 0.4 phase. Modeling the light curves with two spot model indicate that nearly two equal sized spots at relatively low latitude could explain the observed light variation during the epoch 1996.09, whereas unequal sized spots lying in opposite hemispheres are needed to reproduce the light curve for the epoch 1997.08. The brightness at minimum and maximum seem to follow the suggestion of Henry et al. (1995) *i.e.* it decreases at minimum and increases at maximum. This behaviour in turn reflects that changes in the amplitude are mainly due to redistribution of spots on the stellar surface rather than overall changes in the level of spottedness. The coverage of the fractional spot area show close agreement with previously reported spot area obtained by modeling of photometric light curves with two spot model (Rodono et al. 1986). We have not found explicit variation in (B-V) and (V-R) colour indices for this star.

4.2. UX Ari

The well known non-eclipsing active binary UX Ari has been frequently observed at different wavelengths by several investigators in the past two decades (see e.g. Raveendran & Mohin 1995; Padmakar & Pandey 1996). The double-lined spectroscopic binary system UX Ari comprises a hot G5 V and an active cool K0 IV stars. From continuous monitoring of UX Ari during 1988-89, Rodono & Cutispoto (1992) recorded a clear indication of short term variation in its light curve. We used $i = 60°$ for this star while modeling its light curves (Poe & Eaton 1985). BVR observations on UX Ari for the period from Nov 1995 to Feb 1997 are reported here. A visual inspection of its light curve (Fig.2) reveals the existence of two maxima separated from each other by 0.37 in phase, and further that the longitudinal separation is maintained in the next epoch too. Spot parameters as derived from starspot

Table 1. Basic parameters of six RS CVn binary stars

Star	Sp. Type	V_{max}	Ephemeris	T_{phot}[4]	i	u_V	u_R	Comp. Star
V711 Tau	K2 IV	5.691	2,442,766.080 + 2.83774E[1]	4300	33°	0.74	0.57	10 Tau
UX Ari	K0 IV	6.510	2,440,133.766 + 6.43791E[2]	4800	60°	0.66	0.52	62 Ari
IM Peg	K1 V	5.630	2,422,230.992 + 24.649E[3]	4400	60°	0.73	0.57	HD 216635
II Peg	K2 IV	7.306	2,443,030.239 + 6.724183E[1]	4300	34°	0.74	0.57	HD 224930
σ Gem	K1 III	4.134	2,447,227.080 + 19.60447E[1]	4400	60°	0.73	0.57	HD 60318
λ And	G8 IV	3.712	2,443,829.200 + 53.95E[1]	4800	60°	0.74	0.52	ψ And

1 Henry et al. (1995)
2 Raveendran & Mohin (1995)
3 Eaton *et al.* (1983)
4 Poe & Eaton (1995), except for V711 Tau

Table 2. Starspot parameters of six RS CVn binary stars

Star	λ_1	β_1	γ_1	λ_2	β_2	γ_2	γ_p	Total Area(%)
				95-96				
V711 Tau	6.3	29.5	14.1	150.2	32.7	16.7	20.3	6.7
	±5.9	±3.1	±0.5	±4.0	±2.2	±0.4	±0.3	± 0.3
UX Ari	22.8	34.3	23.2	231.7	14.8	8.2	27.2	10.1
	±1.7	±4.8	±0.3	±13.9	±10.7	±0.9	±0.2	±0.3
IM Peg	240.1	55.3	30.4	341.4	47.7	16.1	16.6	10.9
	±0.8	±0.7	±0.2	±1.9	±2.7	±0.3	±0.2	±0.2
II Peg	7.3	1.3	24.9	165.6	6.7	38.6	3.3	15.7
	±2.6	±1.1	±0.8	±1.0	±0.4	±0.3	±0.3	±0.5
σ Gem	30.2	28.3	10.2	158.2	54.7	20.0	8.7	4.4
	±6.1	±12.7	±0.5	±2.1	±2.0	±0.3	±0.3	±0.2
λ And	108.0	61.7	24.3	217.6	49.2	9.9	20.9	8.5
	±1.7	±1.4	±0.4	±7.1	±8.5	±0.5	±0.3	±0.3
				96-97				
V711 Tau	111.9	-3.2	25.4	166.6	45.0	17.6	8.8	7.8
	±3.5	±1.3	±0.8	±3.2	± 1.9	±0.3	±0.4	±0.4
UX Ari	1.2	29.4	26.9	144.2	42.1	15.8	10.3	8.1
	±1.1	±2.9	±0.2	±3.9	±7.5	±0.4	±0.2	±0.2
IM Peg	189.1	55.1	31.7	268.2	6.6	22.0	22.3	14.9
	±1.1	±0.8	±0.2	±1.4	±1.8	±0.3	±0.3	±0.3
II Peg	22.0	6.0	34.3	124.2	36.4	26.5	15.3	15.7
	±1.1	±0.4	± 0.2	±1.1	±0.7	±0.2	±0.5	±0.3
σ Gem	26.9	55.9	15.7	182.4	5.3	14.3	28.6	9.5
	±4.2	±4.1	±0.4	±3.6	± 3.7	±0.4	±0.3	±0.3

models seem to indicate movement of two spots close to each other and also towards lower longitudes. This apparently contradictory results may be due to unreliable determination of the spot latitudes through starspot modeling. The value of maximum brightness during the epoch 1997.08 is found to be ~0.82 mag. This value of maximum brightness is the same as obtained at the mean epoch 1989.10 by Raveendran and Mohin (1995). We have also recorded variation in (B-V) colour index with an amplitude of ~0.05 mag. Our observations confirm the definite anti-correlation between ΔV light curve and (B-V) colour index curve, as reported by several investigators (Zeilik et al. 1982 Rodono & Cutispoto 1992; Raveendran & Mohin 1995). The unexpected anti-correlation in (B-V) and constancy in (V-R) colour indices may be useful to solve the ambiguity in determining whether the variation in (B-V) is due to flaring and facular origin (Rodono & Cutispoto 1992) or whether it is merely due to fractional contribu-

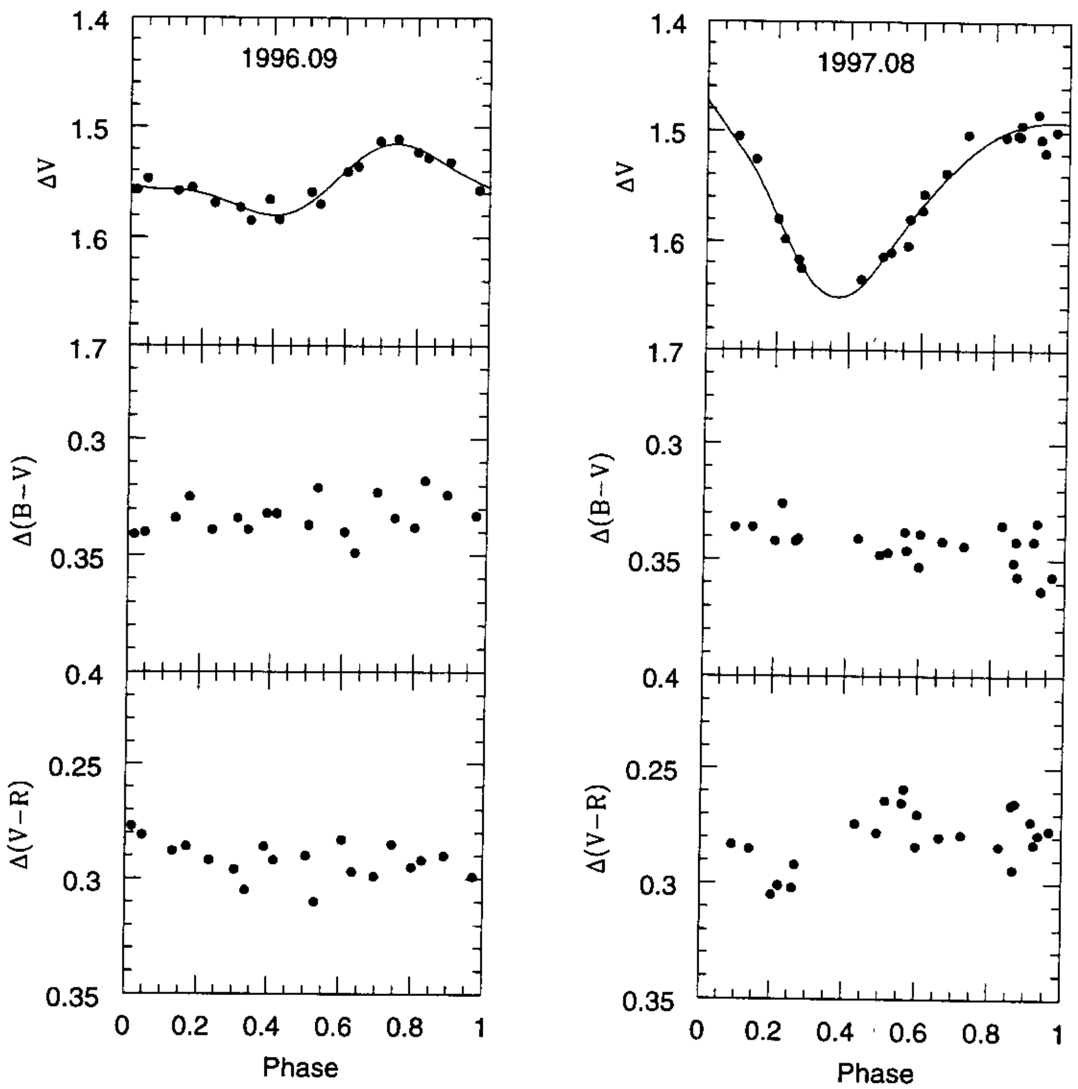

Fig. 1. BVR light curves of RS CVn star V711 Tau during epoch 1996-97.

tion of the hot star in the blue region to the composite light (Raveendran and Mohin 1995).

4.3. IM Peg

IM Peg is one of very active bright members of long period RS CVn group. The coordinated photometry and spectroscopy of this star clearly indicate anti-phase variation of H_α emission line (Dempsey et al. 1996). The light curves obtained by Eaton et al. (1983) and Strassmeier et al. (1989) showed remarkable variation in the amplitude (from 0.11 to 0.24 mag.) without showing any significant variation in the shape. The orbital inclination $i = 60°$ was adopted for IM Peg from Poe & Eaton (1985). Our observations for the period 95-97 support this picture. For the epoch 1995.89 our observation concide with those of Strassmeier et al. (1997). Both observations give similar results except the difference in the phase of minimum light which is the result of using different ephemeris. The amplitude in V band for the epoch 1996.9 is $\sim$ 0.38 mag, which is significantly larger than that found by previous observers. Our photometric observations indicate movement of light minima towards a lower phase. Although, the observed light curves appear nearly symmetric, two spots were needed to fit them, perhaps on account of the deep minima. Our two years observation reveal a remarkable variation in (B-V) as well as (V-R) colour indices for the epoch 1995.9, however, similar kind of variation in colour indices are not seen during the next observing epoch (see Fig.3). We have modeled the (V-R) colour index curve to obtain spot temperature ΔT, the difference between the photosphere and the spot, comes out to be 1130$\pm$35 K ,

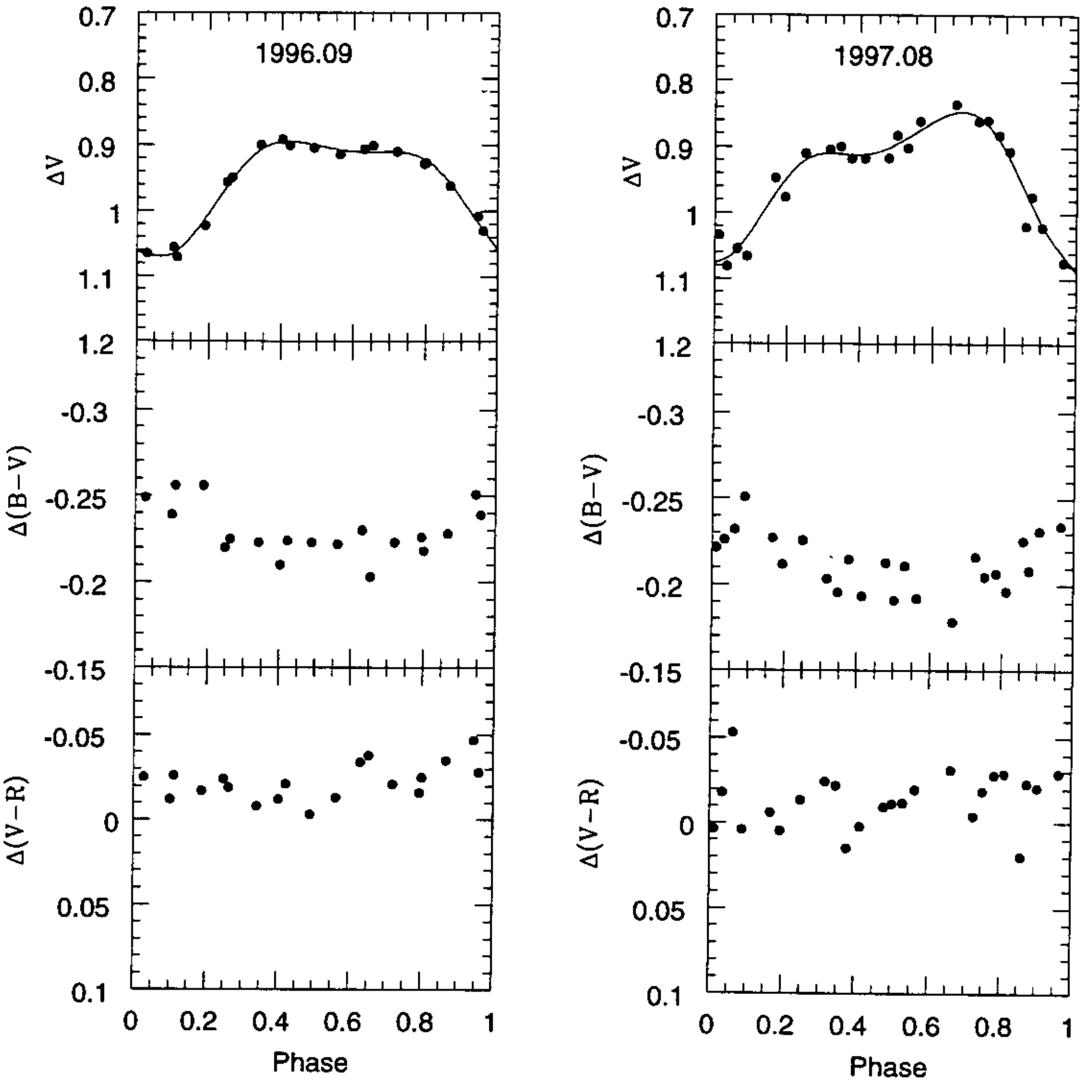

Fig. 2. BVR light curves of RS CVn star UX Ari during epoch 1996-97.

whereas Poe & Eaton (1985) obtained $\Delta T \sim 920 \pm 100$ K for this star.

4.4. II Peg

It is one of the most active RS CVn stars, and it has been frequently observed by several investigators at different wave lengths (Rodono et al. 1986; Strassmeier et al. 1988; Mohin & Raveendran 1993b; Henry et al. 1995; and references therein). Simultaneous photometric and spectroscopic observations indicate strong correlation between light variation and the strength of TiO bands , whereas H_α emission line strength was found to be anti-correlated with the photometric variation(Mohin & Raveendran 1993b). Following Poe & Eaton (1985) and Henry et al. (1995) we have adopted a value of $i = 34°$ for the orbital inclination. Our results on BVR observations for II Peg carried out during Nov 1995 to Feb 1997 are displayed in Fig.4. Seasonal variations in the amplitude, shape and phase of minimum light are evident from this figure. The light curve which showed double peak during the epoch 1995.89, turned in to a near sinusoidal with high amplitude for the epoch 1996.89. The (B-V) and (V-R) colour indices seem to be correlated with visual amplitude V *i.e.* the star was bluer at maxima and redder at minima. However, the brightness at the maximum and the minimum for II Peg does not follow Henry's et al.(1995) picture. The modeling of the (V-R) colour index curve for the epoch 1985.89 gives the value of $\Delta T \sim 740 \pm 45$ K. The derived value of our ΔT falls quite close to the lower limit of the range of values ($\sim$700 to $\sim$1000 K) obtained by other investigators (Poe & Eaton 1985; Vogt 1981; Byrne et al.

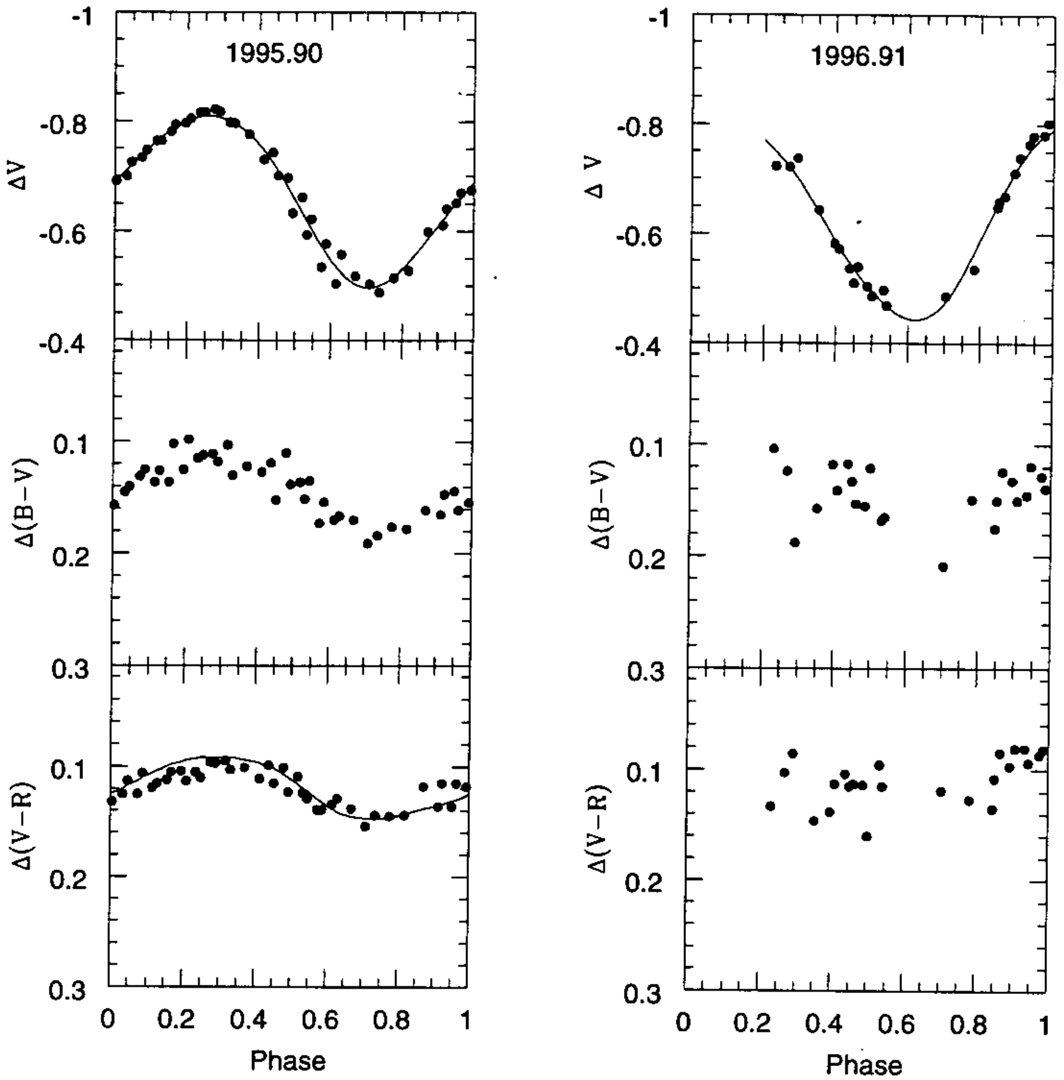

Fig. 3. BVR light curves of RS CVn star IM Peg during epoch 1995-96.

1987) from modeling of the (V-R) colour index curves. Recently O'Neal, Saar and Neff (1998) have reported the first spectroscopic evidence of the multiple spot temperature for this star. From TiO molecular band observations they have found that spot temperature varied between ~3350 to 3550 K during the epoch of September 1996 to October 1996, whereas the starspot filling factor was constant ($f_s \sim 55\% \pm 5\%$). Our photometric observation carried out during nearly the same epoch (1996.89) give different results probably due to the different modeling techniques applied.

4.5. *σ Gem*

It is one of the brightest RS CVn binary star. A systematic photometric study of this single-lined spectroscopic binary has been carried out by Strassmeier et al. (1988), and by Henry et al. (1995). Dempsey et al. (1992) introduced a cross correlation technique to combine informations contained in the line profiles with those of the broad band optical photometry for a reliable determination of spot latitude and other spot parameters. The cross correlation technique indicates that spots occupy relatively higher latitude regions (~ 30° to 60°). In the past all light curve have been modeled using $i = 60°$ (Strassmeier et al. 1988; Henry et al. 1995) , therefore, we also used same value while modeling its light curves. Our result of BVR observations is shown in Fig.5. A substantial variation in the light curves of σ Gem within a year is discernible from the figure. The light curve with single minimum for the epoch 1996.06 turns into a double peaked symmetric one during the next observing epoch,1997.14. There is too small vari-

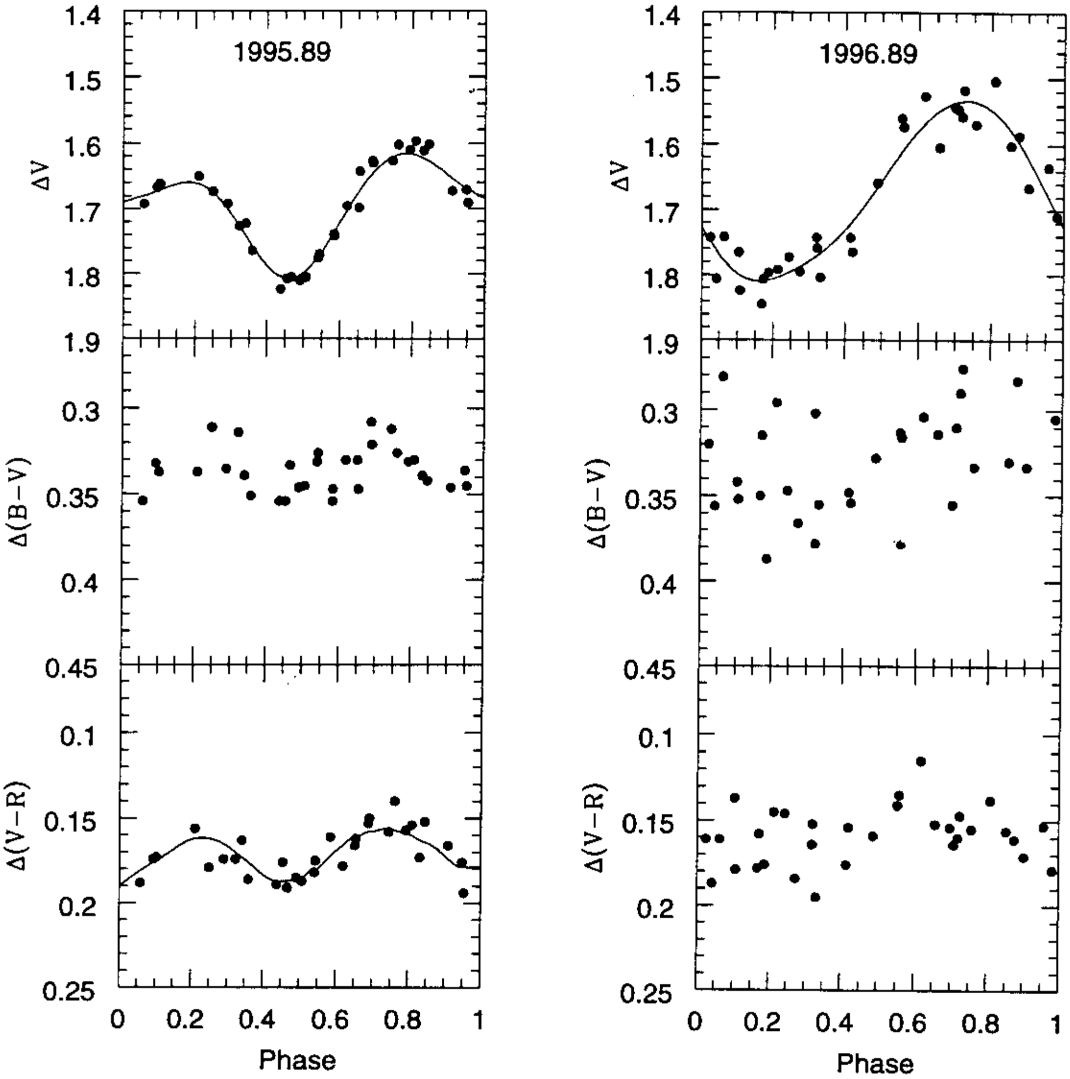

Fig. 4. BVR light curves of RS CVn star II Peg during epoch 1995-96.

ation in the colour indices of this star to allow us to determine reliable values of the spot temperature. The brightness at minimum and maximum are exactly the same as found earlier by Henry et al. (1995).

4.6. λ And

It is among the brightest (V=3.82) of all known chromospherically active binaries discovered so far. Generally most of RS CVn binaries are found to be rotating synchronously(Hall & Henry 1990), but λ And reveals very large asynchronous (P_{rot}/P_{orb} ~2.6) motion which is rather unusual among RS CVn binaries. λ And is a source of strong Ca II H and K and H_α emission lines and these are found to be strongly correlated with the optical light variation (Henry et al. 1995). Historically, the light variability of this star was recorded in the mid 1930s, and subsequently observed by different groups (Bopp & Noah 1980; Dorren & Guinan 1984; Hall et al. 1991; Henry et al. 1995 and references therein). The orbital inclination of the λ And is not a well-known quantity, we used i = 60° for spot modeling following Henry et al. (1995). Our BVR observation were carried out during Nov 1995 to Jan 1996 is shown in Fig.1f. Previous observations show a variation in V amplitude between 0.05 to 0.23 mag. This in turn implies that during our observations λ And was in the stage of moderate activity . The extracted spot parameters from the observed light curves as given in the Table 2, favour the presence of one large spot and another small starspot laying at relatively high latitude to explain the observed light modulation. Our results do not show any significant variation in (B-V) colour index, whereas a

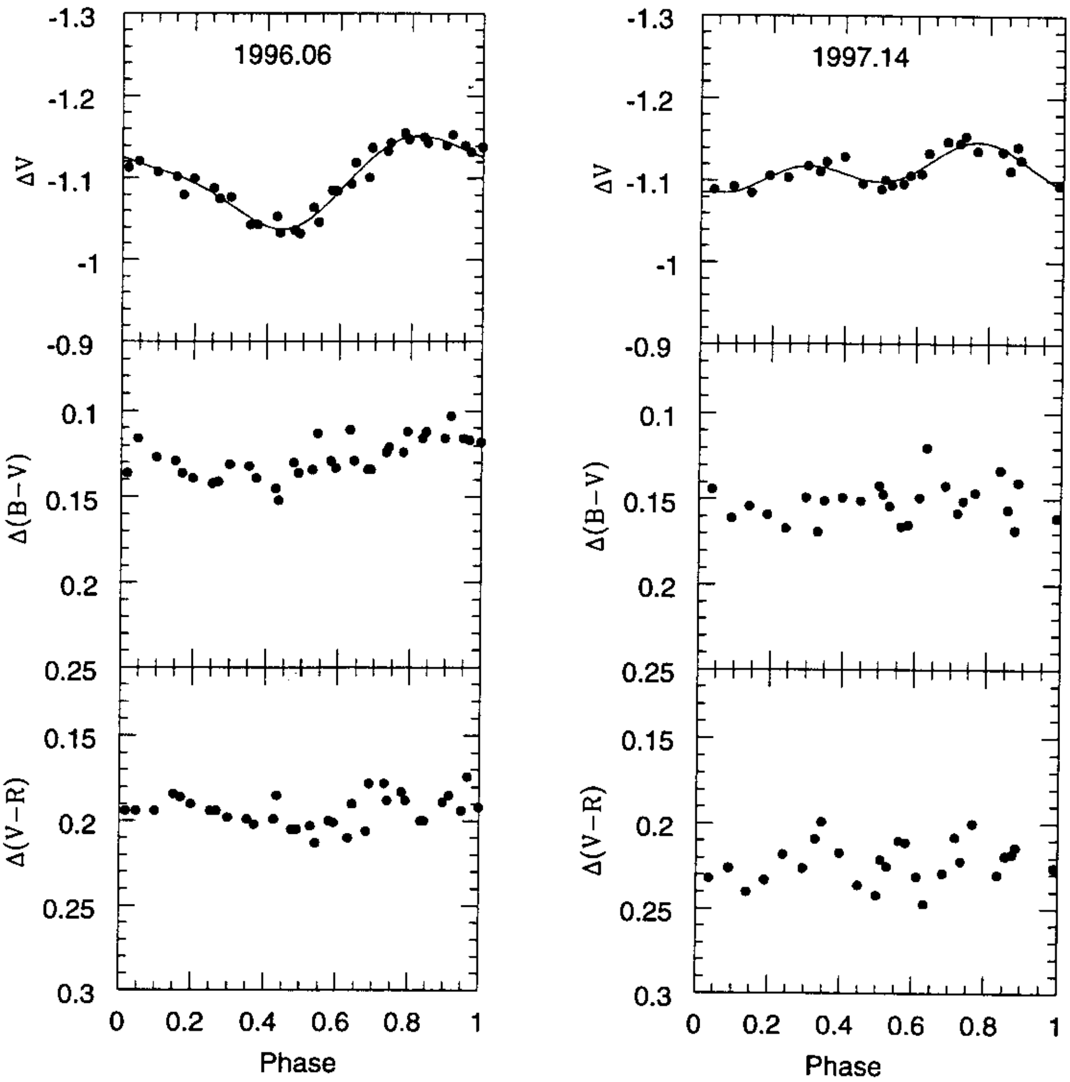

Fig. 5. BVR light curves of RS CVn star σ Gem during epoch 1996-97.

marginal variation in (V-R) colour index can be seen from Fig.6. Modeling of (V-R) colour index curve gives a value of $\Delta T \sim 800 \pm 30$ K while Poe & Eaton (1985) obtained $\sim 1050 \pm 100$ K for the of epoch 1980.7.

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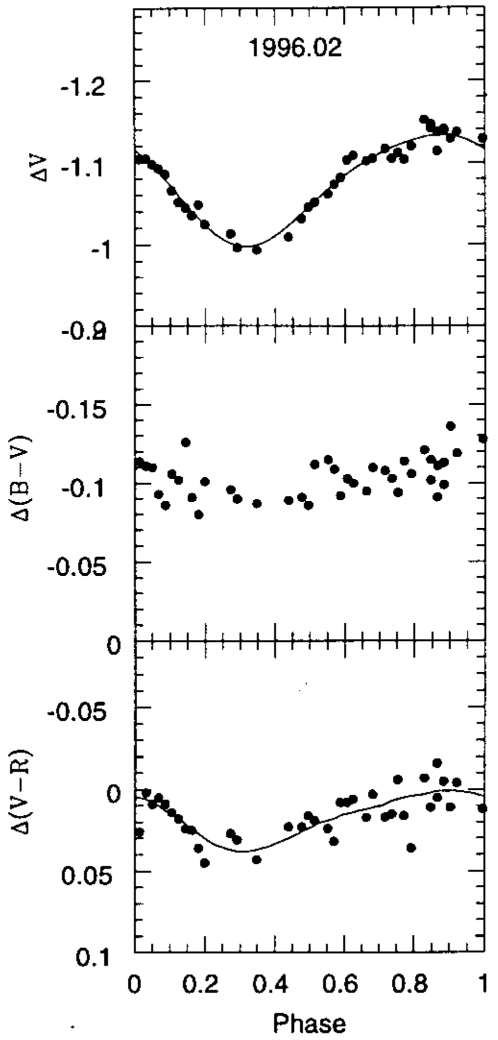

Fig. 6. BVR light curves of RS CVn star λ And during epoch 1995-96

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