Astron. Astrophys. 344, 111–116 (1999)

ASTRONOMY AND ASTROPHYSICS

Polarimetric and spectroscopic study of the weak-emission T Tauri star V 410 Tauri

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Received 2 October 1998 / Accepted 4 January 1999

Abstract. Results of the polarimetric and spectroscopic observations of the weak emission T Tauri star V 410 Tau are presented. The linear polarization and position angle are found to show variability with a period corresponding to the star's rotational period. It is also found that the polarization reaches a maximum near the light minimum. Modelling of the V and R light curves shows that two adjacent spots, occupying a total fractional area of 0.23 and with a temperature 750 K cooler than the photosphere, could account for the observed light variability. We attribute the periodic variability in linear polarization to the variable illumination of an optically thin circumstellar envelope by the rotating spotted star.

The Hα line is found to vary from shallow absorption to emission with the maximum emission strength at the minimum light, and vice versa. The Li I 6708 Å absorption equivalent width, which is consistent with that of the other T Tauri stars, is found to show no appreciable variation with the photometric phase.

Key words: stars: activity – stars: individual: V 410 Tau – stars: pre-main sequence – stars: starspots

1. Introduction

V 410 Tau (HDE 283518, BD +28°637) is one of the best studied T Tauri star. It has a relatively weak Hα emission and very little infrared excess (Cohen 1974; Rydgren et al. 1984; Rucinski 1985). These properties, which are shared by some other T Tauri stars also, suggest that V 410 Tau is a member of the naked T Tauri stars (Walter 1987), now known as Weak emission T Tauri Stars (WTTS). The photospheric spectrum of V 410 Tau was classified as K7 by Cohen & Kuhi (1979) and as K2 by Basri & Batalha (1990). V 410 Tau exhibits large light variations, up to 1 mag in V (Rydgren & Vrba 1983).

Radio continuum observations show V 410 Tau to be highly variable. Beiging & Cohen (1989) measured the radio flux densities at monthly intervals over a one-year period with the VLA and found evidences for the modulation of the radio emission with a 0.933 day period, which is about half the optical period. The radio emission is probably due to non-thermal gyro-synchrotron induced by strong stellar magnetic fields (Stine et al. 1988). V 410 Tau is also a variable X-ray source; Strom & Strom (1994) have found from their ROSAT PSPC observations that $L_X = 1.3\times10^{31}$ erg s^{-1} and noted changes in L_X by a factor of about 2.

The binary nature of V 410 Tau was detected by Ghez et al. (1993). The companion, which is at a projected separation of 0.123 arc sec, contributes about 14% of the light at K band.

Welty & Ramsey (1995) found large amplitude quasi-sinusoidal radial velocity variations at the stellar rotation period in V 410 Tau arising, probably, due to the large-scale photospheric temperature inhomogeneity caused by cool spots.

Petrov et al. (1994), who made a detailed photometric study of V 410 Tau, refined the photometric period as 1.872 days. They also found a correlation between the TiO band strength and stellar brightness such that the band strength was the highest when the star was faintest. Despite its pre-main sequence status, most of the observational properties of V 410 Tau, like the photospheric spot distribution and Hα emission strength variation, are similar to that of the evolved RS CVn binary systems.

Here we report the contemporaneous polarimetric, spectroscopic and photometric observations of V 410 Tau obtained during March-April 1993.

2. Observations

From the extensive photometric observations available in the literature, it is known that the amplitude and shape of the light curves of V 410 Tau remain more or less stable for years together. The main aim of the present photometric observations was limited to obtaining the shape and amplitude of the light curve close to the epochs of the Hα and polarimetric observations. The observations in the V band were carried out with the 75 cm telescope of Vainu Bappu Observatory (VBO), Kavalur, on seven nights during March 1993 with BD +27°651 as the comparison star. The results of the observations are given in Table 1; each value given in the table is the average of two or three measurements. Due to the poor sky conditions prevalent during the observations and large airmasses involved, the typical uncertainty of a value is rather high, around 0.015 mag.

The polarimetric observations were made with the PRL-polarimeter (Deshpande et al. 1985) attached to the 236 cm telescope of VBO. The observations were obtained on eight

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Table 1. V magnitudes of V 410 Tau

JD 2440000+	Phase	V ±0.015
9064.144	0.500	10.630
9065.113	0.017	11.232
9066.087	0.537	10.665
9067.104	0.080	11.200
9068.097	0.611	10.680
9069.090	0.142	11.060
9070.107	0.685	10.803

Table 2. BVR polarimetry of V 410 Tau

JD 2440000+	Band	P%	θ°
9059.129	V	0.37±0.09	138±4
9060.108	V	0.20±0.05	124±7
9061.125	B	0.47±0.13	168±8
	V	0.47±0.02	172±7
9063.111	V	0.48±0.05	4±7
9064.109	V	0.20±0.02	172±9
9065.120	B	0.24±0.12	169±17
	V	0.30±0.05	160±8
	R	0.45±0.07	175±11
9066.108	V	0.33±0.04	166±8
9067.097	V	0.27±0.10	143±10

Table 3. Equivalent widths of Hα emission and Li I absorption in V 410 Tau

JD 2440000+	Photometric phase	Hα (EEW) ±0.05 Å	Li I (EW) ±0.04 Å
9049.121	0.48	−0.16	0.55
9050.099	0.00	1.93	0.60
9051.100	0.53	0.19	0.53
9051.271	0.62	0.26	0.58
9052.128	0.08	2.37	0.52
9079.132	0.51	0.45	0.53
9081.097	0.56	0.53	0.52
9082.094	0.09	1.28	0.61

consecutive nights during March 1993, mostly in the V band. Table 2 gives the journal of observations of linear polarization (P%) and position angle (θ°) in the equatorial coordinates. The errors in P% and θ°were derived from the errors in the observed and instrumental Stokes Q and U values.

Spectroscopic observations in the regions of Hα and Li I 6708 Å were carried out during March-April 1993, near-simultaneously with the photometric and polarimetric observations, using the 102 cm telescope of VBO. The spectrograph setup gives a resolution of 1.38 Å/pixel. Table 3 gives the details of the spectroscopic observations; the Hα emission equivalent width (EEW) and the Li I 6708 Å absorption equivalent width (EW) determined from the spectra are also given in the table.

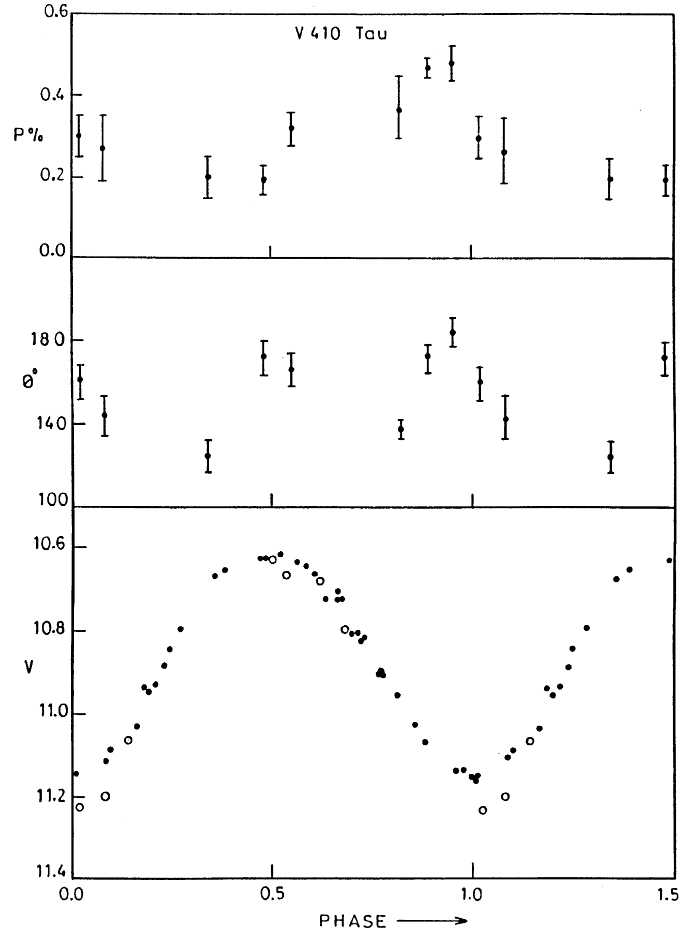

Fig. 1. Plots of V band linear polarization and position angle of V 410 Tau phased with the period. The lower panel is the overlapping photometry

3. Discussion

3.1. Light variability

A striking property observed in V 410 Tau is the stability of its spotted regions. From the photometric observations obtained between 1986 and 1992, Petrov et al. (1994) found that the shape and amplitude of the light curves of V 410 Tau do not change rapidly and in fact both remain stable over several hundred rotational periods, indicating the long-lived nature of the spot group. In the lower panel of Fig. 1 the present observations are plotted along with that of Petrov et al. (1994), obtained during the later part of 1992, using the ephemeris:

$$JD(Hel.) = 2446659.4389 + 1^{\mathrm{d}}.872095E.$$

The open circles indicate the present observations and the filled circles that of Petrov et al. (1994). From the figure it is seen that the shape of the light curve has not changed appreciably from the later part of 1992 to March 1993. The light minimum and maximum occurred at the same respective phases during both the periods. This indicates that the surface distribution of spots did not change significantly within the two epochs. A close scrutiny of the light curves during the period from 1986

Table 4. Spot parameters of V 410 Tau

Spot number	Polar distance (°)	Longitude (°)	Radius (°)	T_{spot} K	Fractional area
1	41±2	327±5	45±3	3650±75	0.156
2	67±11	52±7	30±4	3650±75	0.070

to 1992 shows that the minima remained more or less around $0\overset{p}{.}0$ and the maxima around $0\overset{p}{.}4$, and the magnitudes at maxima and minima, and the shapes of the light curves showed only slight variations. The present observations show that the light minimum in March 1993 was deeper by about 0.04 mag than that in the later part of 1992. The stability of light curves over several hundred rotational period is also found in other WTTS, like V827 Tau and V830 Tau (Grankin et al. 1995), which contrasts with the rapid changes within a few rotational periods observed in classical T Tauri stars (Mekkaden 1998).

For a better understanding of the polarimetric, photometric and spectroscopic variations, the photometric observations obtained by Petrov et al. (1994) during the later part of 1992 were subjected to spot modelling. A modified version of the spot modelling program by Mohin & Raveendran (1992) was used to derive the spot parameters. The computer program employs the method of least squares to model the light curves using differential corrections to the various parameters to arrive simultaneously at the best fit values, including the temperature, assuming that the light variation is caused by a limited number of spots. In WTTS irregular flare activity affect both the U and B light variations, obscuring the periodic light variations in these bands (Herbst et al. 1994), and hence only the V and R light curves were used for spot modelling. The present data were not included in the modelling since they consist of only a few measurements in V band. The photospheric temperature was taken as 4400 K and the inclination of the rotational axis i as 70°(Rice & Strassmeier 1996). The limb darkening coefficients used in V and R were 0.77 and 0.61, respectively (Claret & Gimenz 1990). From the light curves of V 410 Tau available in the literature the maximum observed brightness in V and R are found to be V = 10.60 and R = 9.90, and these were assumed as the unspotted magnitudes in the respective bands. The spot parameters were derived by solving the two light curves simultaneously and are given in Table 4. In Fig. 2 the computed light curves are plotted along with the observations. The standard deviation of the fit σ is comparable to the scatter in the light curves.

The present analysis indicates the occurrence of two adjacent spots, one centred around 50°and the other around 25°latitudes, covering a total fractional area of 0.23. The spots are found to be cooler than the photosphere by 750 K. Petrov et al. (1994) have also modelled the same set of observations and derived the temperature of spots using two methods, namely the blackbody approximation for the spotted and the photospheric regions and the empirical calibration of $V - R$ and T_{eff} by Hayes (1978). The former assumption gives a spot temperature 800±200 K cooler than the photosphere, which is similar to

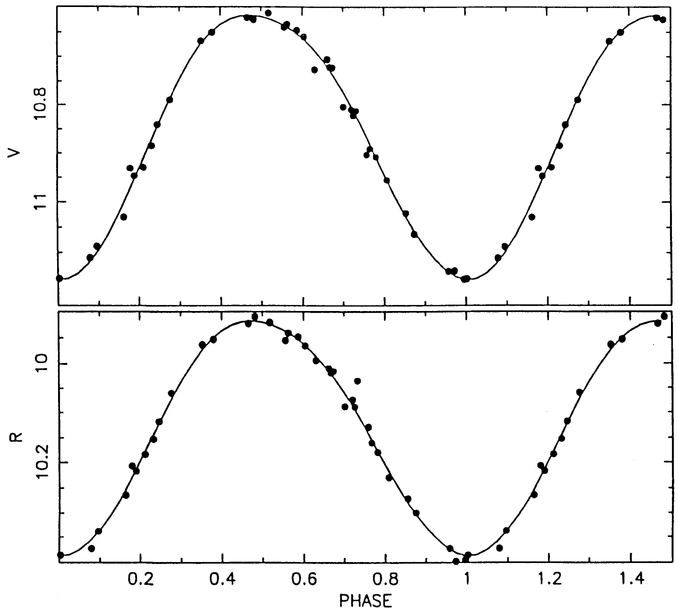

Fig. 2. Plots of V and R light curves of V 410 Tau. The smooth continuous lines represent the computed light curves

the value obtained by us, while the latter gives a temperature 1400±100 K cooler than the photosphere.

From the spot modelling of active stars, Mekkaden & Raveendran (1998) have found that the derived polar distance and radius depend on the number of spots assumed and the only parameter which is not significantly affected is the spot temperature. Using a simple spot model Rydgren & Vrba (1983) found that a spot occupying a fractional disk area of 0.25 and cooler than the photosphere by 600 K described the light variations of V 410 Tau. Vrba et al. (1988) used a two-component spot model to account for the observed light variations of V 410 Tau. They found that the spots had temperatures 1000–1400 K less than the photosphere and covered up to 42% of the stellar surface. Herbst (1989) used a constrained two-spot model to fit the observed light curves obtained during 1981 to 1989. He found that two large spots with radii ∼40°and temperatures 3100 K were present on the star for at least six years. The derived temperatures and areas of spots by various investigators differ due to several reasons, like the actual changes in spot distribution at different epochs and the methods adopted for spot modelling.

Doppler imagings of the spot distribution on V 410 Tau were done by several investigators (Joncour et al. 1994; Strassmeier et al. 1994; Hatzes 1995; Rice & Strassmeier 1996). The Doppler images obtained by Joncour et al. (1994) from the observations of the resonance line of Li I 6708 Å in January 1990 suggested the presence of a large, nearly-polar spot and two comparatively lower latitude spots. The V light curve synthetized from the Doppler images by them also agrees with the photometric observations of Herbst (1989). The light curve had a maximum of 10.70 mag, 0.10 mag fainter than the maximum so far observed, indicating the presence of cool spots on the hemisphere seen at the light maximum also. The present light curve analysis also shows the existence of a large spot around the same

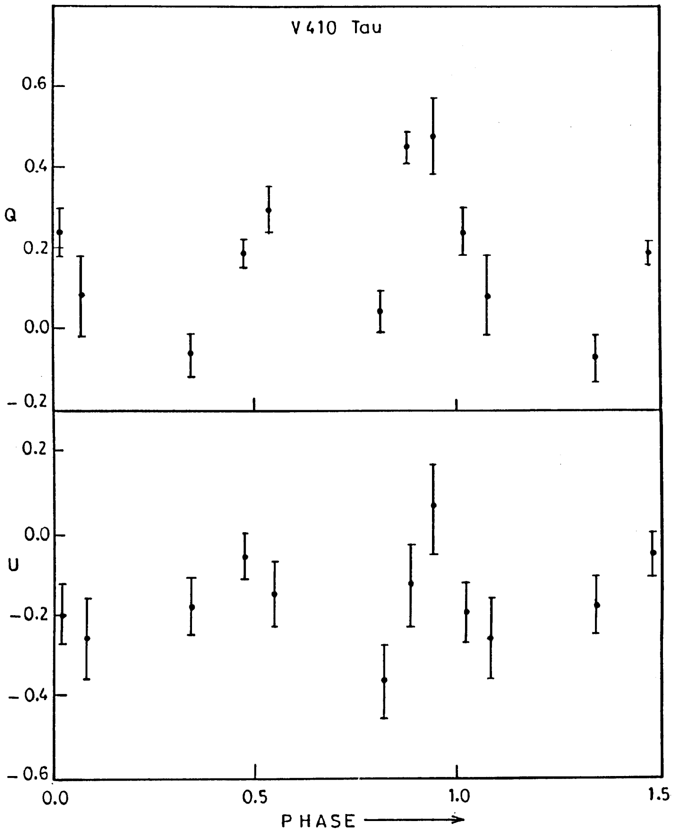

Fig. 3. Plots of the V band Stokes parameters Q and U of V 410 Tau phased with the period

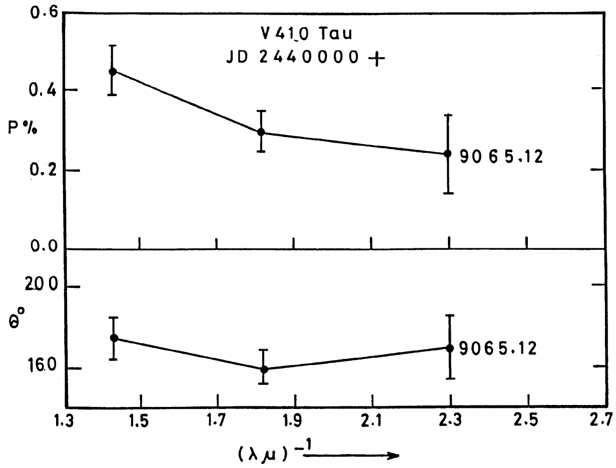

Fig. 4. Plots of linear polarization and position angle of V 410 Tau against the corresponding inverse of the effective wavelength of the filter band

longitude; but the latitude and the temperature of the spot differ in the two cases.

Strassmeier et al.'s (1994) spectroscopic observations used for the Doppler imaging were also obtained during November 1992 coinciding with the photometric observations analysed here. They find that V 410 Tau had surface inhomogeneities which were both cooler and hotter when compared to the ambient photosphere. The temperature of the cooler, high latitude feature was 3200 K. The synthetic broad band photometry from the line profiles gave them an amplitude of 0.37 mag in V, incompatible with the actually observed value of 0.53 mag.

3.2. Linear polarization

Fig. 1 shows the plots of P% and $\theta°$given in Table 2 and the quasi-simultaneous V band photometry given in Table 1 against the phase computed using the ephemeris given before. From the figure it is seen that P% shows a periodic variation that is in anticorrelation with the light variation, in the sense that P% tends to be larger close to the epochs of minimum light. The variation in $\theta°$also exhibits a periodic trend. The maximum of both P% and $\theta°$do not coincide exactly with the minimum of the light curve; apparently, there is a slight phase shift of $\sim 0\overset{p}{.}1$ with the maxima of P% and $\theta°$lagging behind the light minimum. Fig. 3 is the plots of the Stokes parameters Q and U against the photometric phase, and both show periodic trends, if we exclude the largely deviating observation obtained on one occasion. In Fig. 4 the P% and $\theta°$ are plotted against the inverse of the effective wavelength of observation. The P% seems to show a trend in the sense that as the inverse wavelength increases the polarization decreases.

Ménard & Bastien (1992) obtained polarization measurements of V 410 Tau on two nights and their values are comparable with the present observations. Only in the T Tauri star RY Lup the periodic polarization variations were observed convincingly (Bastien 1988, Bastien et al. 1988). Bastien et al. (1988) found that a cool spot subtending about 45°and a smaller bright spot could account for the light curve variation of RY Lup. They attributed the polarization to single scattering by dust grains in a circumstellar envelope and the variations in P% and $\theta°$to its variable illumination by the rotating spotted star.

The observations of V 410 Tau show that the star has almost no near infrared excess and very little far infrared emission (Rucinski 1985). Though this indicates the absence of any considerable amount of circumstellar material, the presence of an optically thin circumstellar dust envelope around the star cannot be completely ruled out. Model calculations presented by Raveendran (1991) show that an asymmetric illumination, produced by surface inhomogeneities that are cooler than the photospheric temperature by 1000 K, of optically thin circumstellar dust envelope can produce linear polarization of the order of 0.50%. The modelling of the light curves presented above shows the existence of two cool adjacent spots at comparatively lower latitudes occupying a total fractional surface area of 0.23. Hence the small amplitude periodic variation in linear polarization observed in V 410 Tau is compatible with the variable illumination of a thin circumstellar dust envelope as the star rotates.

3.3. Hα and Li I lines

The resolution employed in the spectroscopic observations is not sufficient to study the line profile variations. The spectra are displayed in Fig. 5 and the corresponding photometric phases

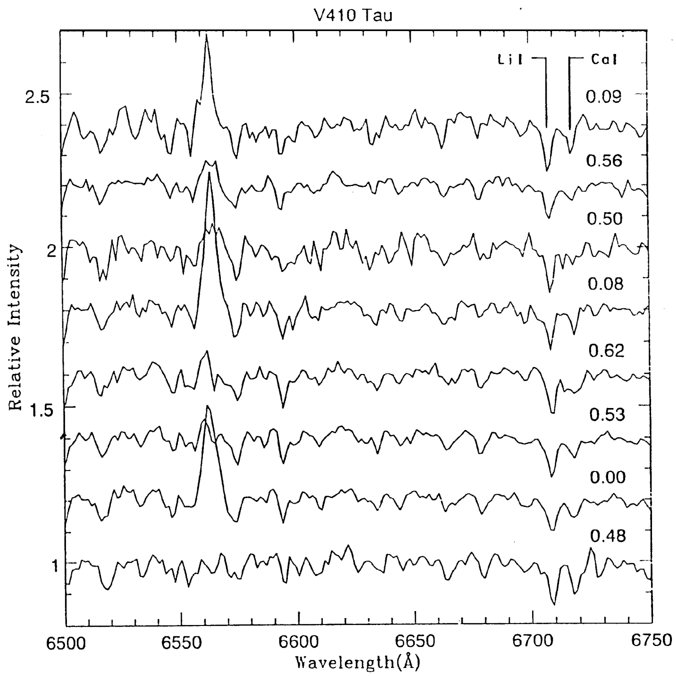

Fig. 5. Hα and Li I spectra of V 410 Tau

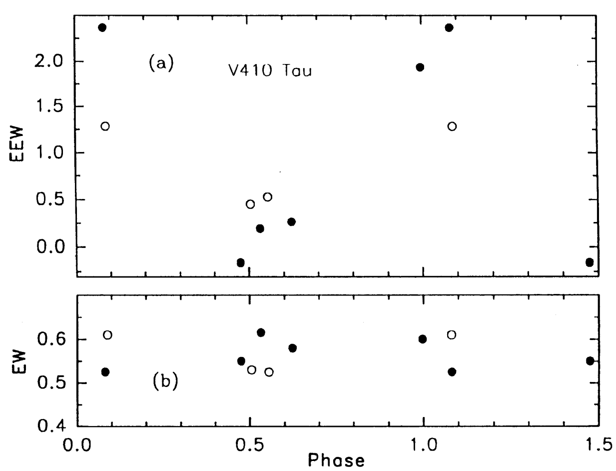

Fig. 6a and b. Plots of (**a**) Hα EEW and (**b**) Li I EW

indicated. Each spectra is shifted arbitrarily along the intensity scale so that the variations in Hα strength can be clearly seen. The Hα line shows variation from a shallow absorption to moderate emission. The maximum Hα EEW observed was 2.37 Å (Table 3). The Hα EEWs and Li I 6708 Å EWs given in Table 3 are plotted against the photometric phase in Fig. 6 where the filled circles denote the measurements obtained during March 1993 and open circles those obtained during April 1993. The figure shows that maximum in Hα emission occurs when the star is at its minimum light, and vice versa. This phenomenon indicates that the chromospheric active regions, like plages, that produce strong Hα emission and the photospheric cool spots are nearly co-spatial, as reported by Welty & Ramsey (1995). As seen from Fig. 6 the Hα EEWs show variations at the maximum level within a period of one month. This implies that though the photospheric cool spots in V 410 Tau have long life spans of the order of years, the changes in the chromospheric active regions take place at much shorter time-scales. The chromospheric active regions are, probably, not always associated with the photospheric spots. The presence of two maxima in the Hα emission observed by Petrov et al. (1994) might be due to the presence of two prominent chromospheric active regions.

From Fig. 6 it is found that the Li I 6708 Å EW does not show any appreciable variation with the photometric phase. The mean of the observed value is 0.56$\pm$0.04 Å. Giampapa (1984) has postulated that the strong magnetic activity in spots would affect the Li I EW as noticed in the Sun. But the high resolution study of Li I line in V 410 Tau by Patterer et al. (1993) indicated only profile variations and no noticeable variation in the line strength, though there is evidence for strong magnetic activity as manifested by cool spots that occupy large area of the stellar surface. However, recent spectroscopic studies by Fernandez & Miranda (1998) showed that the Li I 6708 Å EW had low amplitude variations ($<$0.1 Å) anti-correlated with the light variation.

4. Conclusions

The polarimetric observations of V 410 Tau showed that both P% and $\theta°$have periodic variability in anti-correlation with the photometric variability. From the modelling of the light curve it was found that two adjacent cool spot groups, with a large difference in their sizes and occupying a total fractional surface area of 0.23, could cause the observed variability. The periodic variability in linear polarization is, probably, due to these spots by causing variable illumination of the circumstellar dust envelope.

The observed variations in light, Hα emission strengths, and polarization in V 410 Tau give strong evidence for the presence of highly active cool spots whose life-times are of the order of several years. Though very active, it is surprising to note that the starspots in V 410 Tau do not show any large-scale changes in their distribution on the stellar surface as usually observed in RS CVn objects and young active-chromosphere stars. However, the changes in the chromospheric active regions, as inferred from the changes in the Hα emission strength, occur at time-scales shorter than the life-times of spots in V 410 Tau.

Acknowledgements. I thank Professors M.R. Deshpande and U.C. Joshi for their help in acquiring the polarimetric data. I am grateful to Dr A.V. Raveendran for useful suggestions.

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