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The nature of chromospheric active regions on V410 Tauri

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Abstract. We present spectroscopic observations in the region of $H\alpha$ and Li I lines of the weak emission T Tauri star V410 Tau obtained over 1999/2000, 2002/2003 and 2003/2004 seasons. The emission strength showed rotational modulation during the 1999/2000 season in such a way that the emission strength is maximum at light minimum and vice versa. This indicates that the photospheric and chromospheric active regions overlap over shorter durations of time and the lifetimes of chromospheric active regions are far shorter than the photospheric active regions. But the observations obtained during the 2003/2004 season do not follow the trend observed at earlier seasons. This can be due to the change in the location of chromospheric active regions. Another possibility is the occurrence of a major change in the photospheric active regions that have caused a redistribution of photospheric as well as chromospheric active regions. The Li I EW does not show any appreciable change over the four-year period.

Keywords : pre-main sequence stars, chromospheric activity, starspots

1. Introduction

V410 Tau (BD +28°637) has relatively weak $H\alpha$ emission and very little infrared excess (Rydgren et al., 1984; Rucinski 1985). The lack of strong emission and infrared excess suggest that it is a member of the class of weak emission T Tauri Stars (wTTS). However, V410 Tau exhibits a small infrared excess which is presumably caused by a close

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companion. Ghez et al. (1993) detected the binary nature of V 410 Tau with a projected separation of 0.123 arcsec between the components. The companion contributes about 14% of the light at K band. Due to the large separation, the companion does not have any significant effect on the activity of the primary star.

V410 Tau exhibits large light variations, up to 1 mag in V with a period of 1.87 days (Rydgren & Vrba 1983). The optical variability is caused by the magnetic activity which in turn produces cool photospheric spots, and the inhomogeneous surface distribution of these cool spots rotationally modulates the light. The photometric observations by Vrba et al. (1988) showed that the cool spots responsible for the light modulation are long-lived. They have modeled the light curves and found that the spots have temperatures 1000-1400 K cooler than the photospheric temperature and cover up to 40% of the stellar surface.

Welty & Ramsey (1995) found that the large amplitude quasi-sinusoidal radial velocity variations at the stellar rotation period in V410 Tau arise probably due to the same large scale photospheric temperature inhomogeneity that produces the photometric light variations. They also found that the cooler regions of the photosphere were associated with greater $H\alpha$ emission. A Doppler imaging of the spot distribution on V410 Tau was done by Hatzes (1995) who found that the spot distribution was dominated by a high latitude spot whose centre was offset from the rotational pole of the star. Most of the Doppler imaging reveals the presence of large, cool spots located predominantly near the pole. However, Schuesseler & Solanki (1992) proposed that the dynamo process in the Sun and in magnetically active stars is essentially the same with the difference that in stars the Coriolis force suppresses efficiently the displacements perpendicular to the rotation axis so that the spots emerge preferentially near the polar regions. Petrov et al. (1994) made a detailed photometric and spectroscopic study of V410 Tau. They refined the photometric period as 1.872 days. They also reported the presence of double peaks in the $H\alpha$ emission strength, probably caused by two emitting regions. Fernandez & Miranda (1998) carried out high resolution study of V410 Tau in $H\alpha$ and Li I lines. They detected periodic changes in the narrow component of $H\alpha$ emission in the sense that the maximum emission was observed at light minimum. They also found that the emitting region varies with time scales of months. From polarimetric and spectroscopic observations of V410 Tau, Mekkaden (1999) found that the linear polarization and position angle vary with a period corresponding to the star's rotation period. The polarization reaches a maximum near the light minimum. The periodic variability in linear polarization is attributed to the variable illumination of an optically thin circumstellar envelope by the rotating spotted star. The $H\alpha$ line was found to vary from shallow absorption to emission with the maximum emission strength at the minimum light.

Stelzer et al. (2003) carried out a multi-wavelength study of V410 Tau. They have detected an activity cycle with a period of 5.4 years from their new photometric data and the available photometric data from the literature. They also detected a systematic shift of the minimum observed over a period of ten years and interpreted as due to a latitudinal migration of spots. But the photometric observations prior to 1984 did not show this systematic shift. Fernandez et al. (2004) detected several flares in V410 Tau. They have also studied the variability of $H\alpha$ emission line and suggested that the broad component in $H\alpha$ emission is related to microflaring activity.

The star is an ideal candidate to study the chromospheric activity in a typical wTTS. We have carried out extensive medium resolution spectroscopy of V410 Tau in the regions of $H\alpha$ and Li I lines over a period of four years.

2. Observations

From the large amount of photometric and spectroscopic observations available, we have substantial information regarding the photospheric and chromospheric activities in V410 Tau. The stability of the photometric light curve over many years is an important aspect of this star. The light minimum that corresponds to the maximum activity remains more or less at the same photometric phase indicating a long lifetime of spot groups. Any slight shift in the minimum phase can be due to the change in the centre of activity. The $H\alpha$ emission strength exhibits rotational modulation at times. In order to investigate the nature of $H\alpha$ emission variation, we have carried out extensive spectroscopic observations over a period of four years. Spectroscopic observations in the region of $H\alpha$ and Li I lines were carried out on 22 nights; 3 nights in 1999/2000, 8 nights in 2002/03 and 11 nights in 2003/04 seasons.

The spectra were obtained using the OMR spectrograph attached to the 2.3m Vainu Bappu Telescope (VBT) at Kavalur. The setup using 1200 lines grating blazed at 7500 Å gives a resolution of 1.3 Å per pixel. The star was observed several times each night to study the short time-scale variations also. The exposure times were typically of the order of 30 minutes so that the S/N ratio was of the order of 80 to 100. The spectroscopic data were analyzed using the Image Reduction and Analysis Facility (IRAF). The extraction of the spectrum from the two dimensional raw image involve the corrections for the electronic bias, dark current, sky and background brightness and non-uniform sensitivity across the detector. The spectra were normalised in the interactive mode to the continuum by manually defining the continuum. The equivalent widths of $H\alpha$ and Li I lines were measured from each spectrum. The resolution obtained with the present setup was not sufficient for a detailed profile analysis and hence only the equivalent width of lines were measured.

The results of the spectroscopic observations are given in Table 1. Column 1 gives the serial number of the spectrum; column 2, the Julian Day of observation; column 3, the corresponding photometric phase; column 4, the $H\alpha$ emission equivalent width along with error and column 5, the Li I line equivalent width with error. The photometric phases are computed using the ephemeris of Petrov et al. (1994):

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

The $H\alpha$ line is in absorption on two occasions and they are denoted by a negative sign in the Table.

Table 1. Equivalent width of Hα emission and Li I absorption in V410 Tau.

Sp. No.	JD 2450000+	Photometric Phase	Hα (EEW) $\pm$0.05 Å	Li I (EW) $\pm$0.05 Å
01	1482.271	0.17	0.94	0.00
02	1482.298	0.18	0.77	0.63
03	1482.324	0.20	0.71	0.00
04	1482.375	0.22	0.41	0.62
05	1482.400	0.24	0.15	0.62
06	1482.428	0.25	0.09	0.66
07	1482.453	0.27	0.05	0.65
08	1509.206	0.56	0.30	0.65
09	1509.233	0.58	0.73	0.58
10	1509.257	0.58	0.92	0.50
11	1509.285	0.60	1.07	0.00
12	1509.318	0.62	1.27	0.00
13	1509.342	0.63	1.39	0.63
14	1509.367	0.64	1.42	0.62
15	1509.390	0.65	1.52	0.66
16	1509.438	0.68	1.51	0.00
17	1597.108	0.51	-0.72	0.52
18	1597.147	0.53	-0.62	0.57
19	1597.199	0.56	0.35	0.55
20	2621.183	0.53	0.41	0.53
21	2621.206	0.54	0.41	0.49
22	2622.160	0.06	1.38	0.64
23	2622.180	0.07	1.42	0.51
24	2622.203	0.80	1.37	0.52
25	2622.223	0.90	1.32	0.56
26	2622.372	0.17	1.10	0.57
27	2669.071	0.11	1.14	0.55
28	2669.092	0.12	1.12	0.59
29	2669.165	0.16	1.18	0.55
30	2669.184	0.17	1.28	0.51
31	2669.267	0.22	1.25	0.54
32	2670.079	0.65	0.88	0.58
33	2670.148	0.69	1.15	0.59
34	2670.168	0.70	1.15	0.00
35	2670.234	0.73	1.07	0.00

Table 1. Continued.

Sp. No.	JD 2450000+	Photometric Phase	Hα (EEW) ±0.05 Å	Li I (EW) ±0.05 Å
36	2670.255	0.74	0.87	0.66
37	2671.077	0.18	0.99	0.59
38	2671.140	0.22	0.92	0.56
39	2671.170	0.23	0.89	0.60
40	2671.240	0.27	0.84	0.65
41	2671.263	0.28	0.84	0.55
42	2708.078	0.95	1.53	0.65
43	2709.084	0.48	0.25	0.54
44	2710.078	0.02	2.57	0.55
45	2710.132	0.04	2.91	0.58
46	2992.093	0.66	1.25	0.61
47	2992.116	0.67	1.16	0.60
48	2992.144	0.68	0.98	0.60
49	2993.072	0.18	0.93	0.59
50	2993.201	0.25	0.94	0.56
51	2993.225	0.26	0.88	0.58
52	2993.306	0.30	0.90	0.55
53	2993.329	0.32	0.88	0.53
54	2994.076	0.72	0.44	0.58
55	2994.103	0.73	0.37	0.59
56	2994.127	0.74	0.30	0.58
57	2994.229	0.80	0.39	0.58
58	2994.253	0.81	0.57	0.61
59	2994.342	0.86	0.64	0.62
60	2994.365	0.87	0.75	0.65
61	2995.074	0.25	0.99	0.62
62	2995.102	0.26	1.03	0.59
63	2995.125	0.28	1.02	0.60
64	2995.196	0.31	1.18	0.64
65	2995.226	0.33	1.32	0.64
66	2995.322	0.38	1.77	0.60
67	2995.345	0.39	1.79	0.60
68	2995.368	0.41	1.75	0.57
69	3027.244	0.43	1.21	0.00
70	3028.121	0.90	1.11	0.59
71	3028.146	0.91	1.00	0.62
72	3029.080	0.41	0.92	0.61
73	3029.105	0.43	0.88	0.60

Table 1. Continued.

Sp. No.	JD 2450000+	Photometric Phase	Hα (EEW) ±0.05 Å	Li I (EW) ±0.05 Å
74	3030.082	0.95	0.86	0.63
75	3030.112	0.97	1.17	0.63
76	3037.073	0.68	0.45	0.61
77	3037.099	0.70	0.30	0.59
78	3038.073	0.22	1.46	0.60
79	3038.097	0.23	1.32	0.60
80	3038.120	0.24	1.29	0.58
81	3038.143	0.26	1.20	0.60
82	3038.167	0.27	1.12	0.61
83	3038.190	0.28	1.04	0.62
84	3038.213	0.29	0.99	0.64
85	3038.236	0.30	0.92	0.62
86	3038.258	0.32	0.82	0.63
87	3039.069	0.75	0.66	0.62
88	3039.096	0.76	0.63	0.63
89	3039.190	0.81	0.61	0.63
90	3039.214	0.83	0.65	0.62

3. Discussion

The long-term stability of active regions on V410 Tau makes it the best candidate to investigate the nature of photospheric and chromospheric activities in wTTS. The large amount of photometric data collected by several investigators during the last three decades show that the photospheric active regions, namely the cool spots, are the manifestations of large scale magnetic activity similar to that observed in sunspots but enhanced by several magnitudes. The broad band light curves, which are attributed to the modulation by cool spots, are nearly stable for years. However, the shape, amplitude and phases of maxima and minima show minor, irregular variations indicating that changes do occur within the spot group. It is observed that the strength of chromospheric emission lines varies within a short time-scale. Hence, for a detailed study of the behaviour of chromospheric activity, the star has to be observed for a longer duration.

3.1 Hα emission

The $H\alpha$ variations observed during our campaign range from a maximum emission of 2.9 Å (probably a mini-flare) to absorption during two measurements in one night. The average of the maximum strengths of $H\alpha$ EEW observed over the three seasons is around

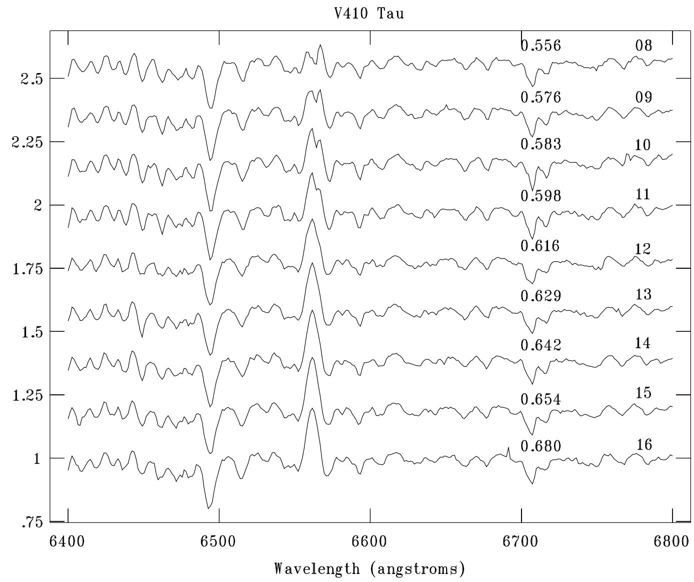

Figure 1. $H\alpha$ and Li of V410 Tau on JD 2451509.

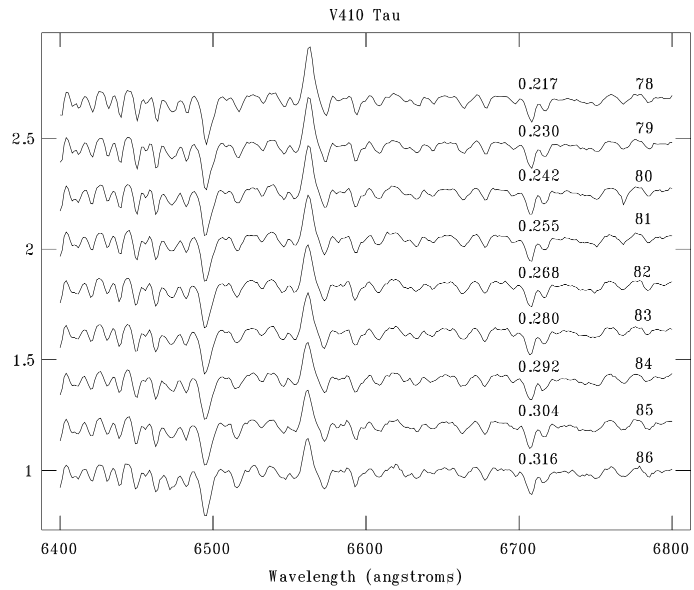

Figure 2. $H\alpha$ and Li of V410 Tau on JD 2453038.

1.6 Å (refer Fig. 3), and hence the $H\alpha$ emission of 2.9 Å may presumably be due to a mini-flare. The star was also observed several times during a few nights to search for

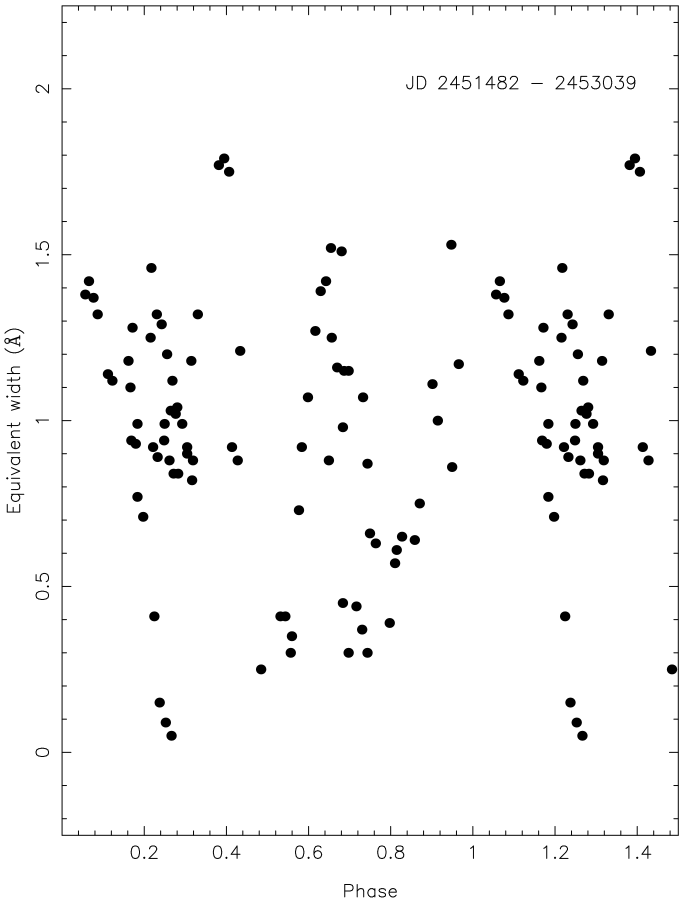

Figure 3. Plot of $H\alpha$ EEW against photometric phase over the 4 year observing period.

short time-scale variations. Figs. 1 and 2 are the plots of spectra obtained on such two nights. Each spectrum is shifted arbitrarily along the vertical-axis. The photometric phases and the serial numbers of spectra are also mentioned in the figures. From Fig. 1 it can be clearly seen that the $H\alpha$ line changes from a double-peaked emission to a strong, symmetric emission within a few hours.

Fig. 3 is the plot of $H\alpha$ EEW against the photometric phase covering all observations over the entire period of 4 years. The strong emission observed on a particular night (2.91 Å) and the absorption on another night were not included in the plot since they are beyond the range of the plot. The plot does not show any appreciable trend in $H\alpha$ EEW with photometric phase except that the $H\alpha$ varies from absorption to an emission strength of around 2 Å. Petrov et al. (1994) and Hatzes (1995) obtained a maximum value of 3 Å in $H\alpha$ EEW in V410 Tau. Hence it can be assumed that the chromospheric active

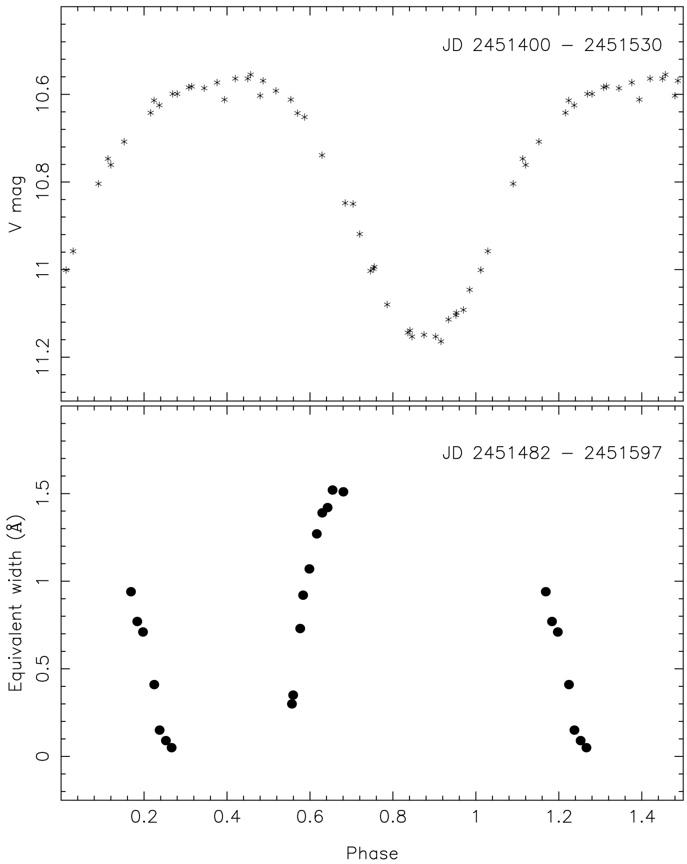

Figure 4. Plots of V band light curve and $H\alpha$ EEW against photometric phase for the season 1999/2000.

regions on V410 Tau during our observations were not very strong compared to the earlier epochs.

Though the photospheric cool spots in V410 Tau have lifetimes of the order of years, the chromospheric active regions that cause the emission lines have shorter lifetimes and sometimes both are not overlapping. So, we have split the data into three groups, each representing shorter durations of the order of three months, namely, for the seasons 1999/2000, 2002/2003 and 2003/2004 in order to investigate the short time-scale variations in chromospheric activity. Fig. 4 is the plots of $H\alpha$ EEW and light variations in V band against photometric phase for the season 1999/2000. The V band photometric observations are taken from Stelzer et al. (2003). The $H\alpha$ emission strengths were maximum at the photometric light minimum and vice versa. This means that the chromospheric active regions were co-spatial with the active spot group. The shape of the $H\alpha$

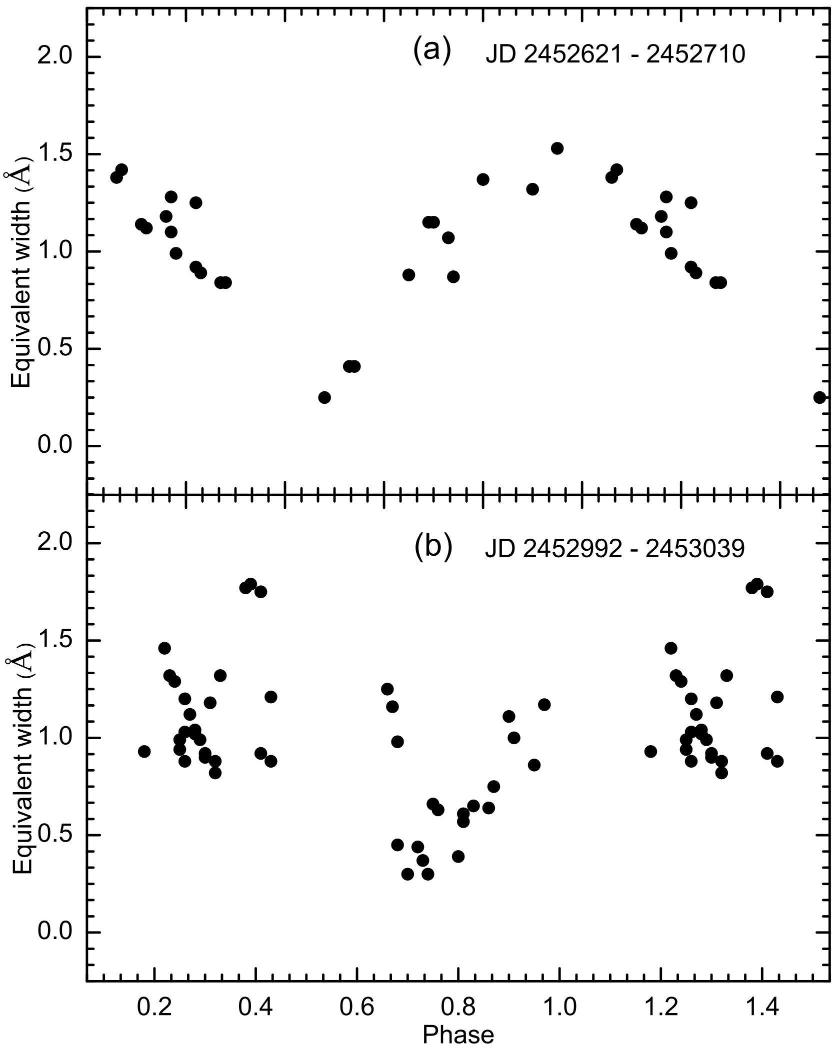

Figure 5. Plots of $H\alpha$ EEW against photometric phase (a) for the season 2002/2003 and (b) for the season 2003/2004.

emission curve is similar to and in phase with that obtained by Fernandez & Miranda (1998).

Fig. 5 contains the plots of $H\alpha$ EEW for the seasons 2002/2003 and 2003/2004 for which no simultaneous photometric data are available. The observations of 2002/2003 also exhibit more or less the same trend as that of 1999/2000. But the plot of $H\alpha$ EEW during the season 2003/2004 show a different picture. The chromospheric active regions

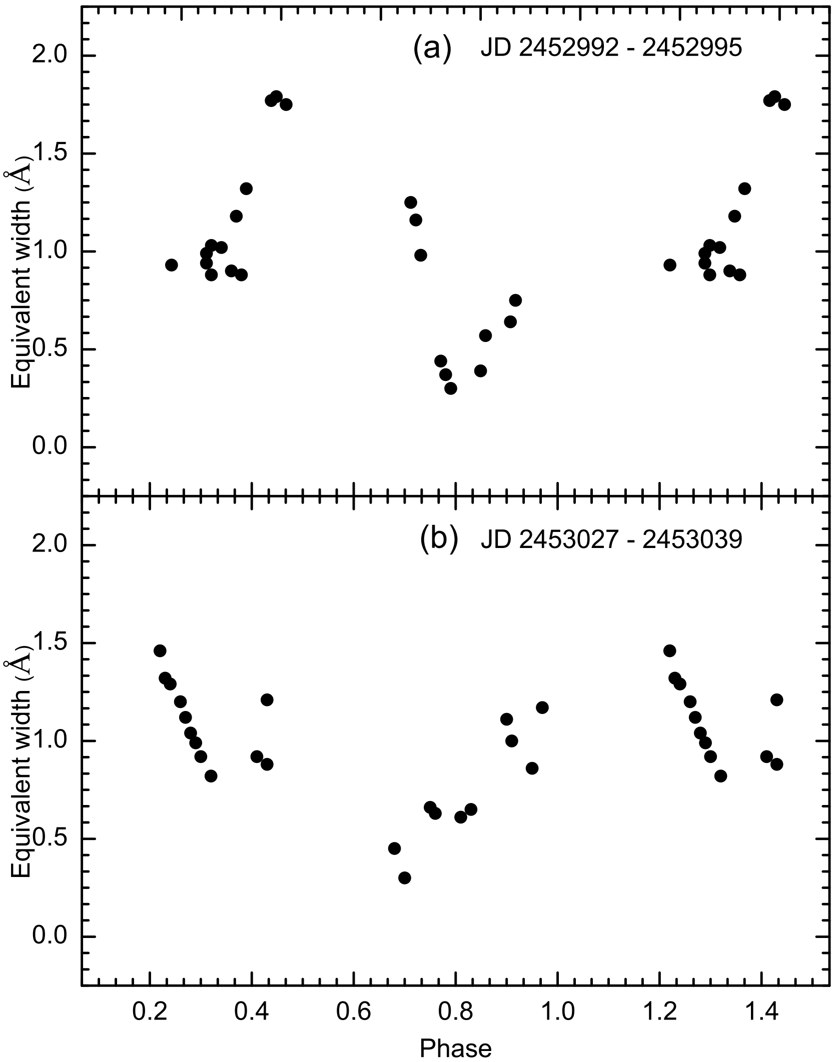

Figure 6. Plots of $H\alpha$ EEW against photometric phase for shorter periods during 2003/2004.

on V410 Tau have undergone a major change between 2002/2003 and 2003/2004 seasons. They are more widely spread and do not exhibit any co-spatial nature with respect to the photospheric spots. A few of the earlier observations by other authors also have shown similar phenomenon. This phenomenon can also occur due to the redistribution of photospheric active regions and that may cause changes in the chromospheric activity. In order to investigate the lifetimes of $H\alpha$ active regions, we have plotted in Fig. 6 the $H\alpha$ emission strengths for shorter durations. It can be noticed from the figure that the nature of active regions change within the two epochs of the curves (a) and (b) indicating

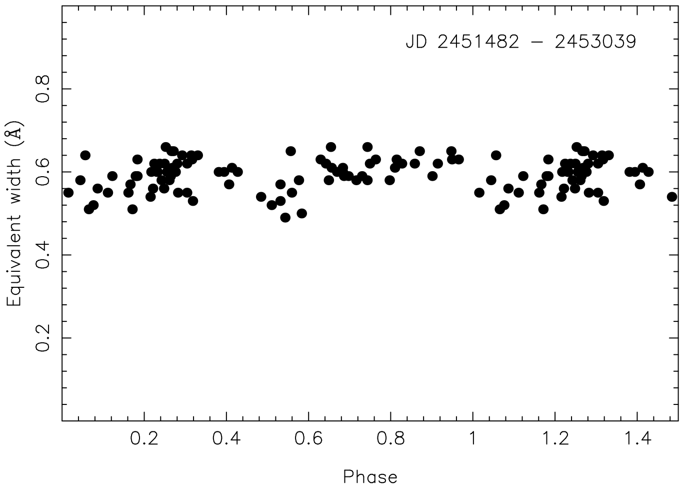

Figure 7. Plot of Li EW against photometric phase over the 4 year observing period.

that the changes in active regions could take place even within a month. We have not observed any strong flare during our entire period of observations.

3.2 Li I 6708 Å line

The Li I equivalent width is plotted against the photometric phase in Fig. 7. The line width does not show any appreciable variation over the entire period of observations. The mean of the observed value is 0.59±0.04 Å, which is slightly larger than the earlier reported values. Giampapa (1984) has postulated that the strong magnetic activity in spots would affect the Li I EW as noticed in the Sun. However, spectroscopic studies by Fernandez & Miranda (1998) showed that the Li I EW had low amplitude variations ($<$ 0.1Å) anti-correlated with the light variation.

4. Conclusions

Extensive medium resolution spectroscopic observations of V410 Tau in the spectral regions of $H\alpha$ and Li I lines were carried out. The observations were obtained over 22 nights during the period 1999/2000, 2002/2003 and 2003/2004. The star was repeatedly observed on several nights to search for short-period variations in activity. The results of the study can be summarized as follows: The chromospheric active regions, inferred from the $H\alpha$ emission, show large variations over the entire period of 4 years. The $H\alpha$ emission strength exhibits a strong anticorrelation with the photometric light curve during some epochs in such a way that maximum emission is observed when the star is fainter and vice versa. This phenomenon is attributed to the presence of chromospheric active regions co-spatial with the photospheric cool spots. Though the photospheric cool spots have lifetimes of several years, the chromospheric active regions have shorter lifetimes. It is noticed that the location and strength of active regions could change within a month. During 1999/2000 and 2002/2003 the emission minimum occurred around 0.50 phase. A major change in chromospheric active regions took place between 2002/2003 and 2003/2004 seasons. A closer analysis of 2003/2004 data showed that the lifetimes of chromospheric active regions could be even shorter than a month. This can be due to the formation of a new chromospheric active region at a different stellar longitude not associated with the photospheric cool spots. Another possibility is the formation of a new spot group, probably short-lived, and the associated chromospheric active region that causes the emission variations.

The $H\alpha$ emission was strong during a particular night (2.91 Å) compared to the average maximum value observed (~ 1.6 Å) during the present observations over a period of 4 years. This may be due to a mini-flare type activity. The $H\alpha$ line was in shallow absorption only during one night implying that most of the time active regions are present on V410 Tau. The emission line showed double-peak at times, usually near the photometric maximum light.

The Li I 6708 Å line EW does not show any appreciable variation over the entire period of observation. The average value observed during the present study is comparatively larger than the earlier reported values.

The present spectroscopic study of V410 Tau gives a few important results. The chromospheric active regions are short-lived compared to the photospheric spots. Hence any attempt to correlate the overall behaviour of chromospheric activity with photospheric cool spots over several years may not yield any significant result. But one can investigate the nature of chromospheric activity over shorter time-scales and usually it is noticed that the chromospheric and photospheric active regions are co-spatial. Sudden formation or reorganisation of chromospheric active regions alter the light curve-chromospheric activity relationship.

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