1981Ap&SS..74...87P

RS CVn-TYPE VARIABLES

I: *Photometry of HR* 1099

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(Received 21 May, 1980)

Abstract. Photometric observation of HR 1099 in *V* and *B* obtained on 18 nights between January and March 1977 is presented. The amplitude of the asymmetric light curve is found to be $0^m.10 \pm 0^m.004$ both in *V* and *B*. On three occasions—namely, JD 2443164.17, JD 2443176.14 and JD 2443177.12—the star brightened by $\sim 0^m.05$. Four Hα spectrograms at 42 Å mm^{-1} dispersion were obtained during October–November 1978. The profile and equivalent width of Hα of 14 November, 1978 suggest a probable major outburst.

Analysis of all available photometry shows that (1) the amplitude and shape of the light curve change in a few orbital periods, (2) the phase of the minimum light migrated towards decreasing orbital phase during the interval JD 2442720 to JD 2443000 and from JD 2443200, there is almost a linear increase of the phase of the minimum light and (3) the phase of the light minimum sometimes shows to and fro behaviour suggesting the migration of the wave is not taking place smoothly.

1. Introduction

Strong H and K emission lines of ionized calcium are the most prominent spectral features in majority of the RS CVn-type close binaries. The space density of these systems is quite high, 10^{-6} systems pc^{-1} sec. The principal characteristics of the RS CVn-type systems are (Hall, 1976): (1) The primary components are of spectral type F–G V–IV and the cooler and more active secondary components are G5-K0V-IV; (2) The orbital periods range from 1 to 14 days; (3) strong H and K emission lines of Ca II with emission widths comparable to those of the absorption lines; (4) some of the systems exhibit wavelike distortions in their light variations, which often migrate to decreasing orbital phases with periods of 10–20 years or more. This phenomenon has been interpreted by Hall (1976) as resulting from extensive star spot activity on the surface of the secondary component. Additionally, Weiler *et al.* (1978) have reported variable chromospheric emission at Lα (1215 Å) and at Mg II h and k (2800 Å) in some of the bright RS CVn-type systems. The HEA01 A-2 low energy X-ray sky survey has shown that many of the RS CVn-type systems are strong coronal X-ray sources (Walter *et al.*, 1980). Steady radio emission has been detected from several RS CVn systems with occasional strong radio flares involving an order of magnitude change in flux (Gibson *et al.*, 1975; Feldman *et al.*, 1978). In addition to the short period (1–14 days) RS CVn-type systems there is a long-period (Hall, 1976) RS CVn group consisting of Ca II emission binaries with periods greater than two weeks and having some of the above mentioned characteristics. Most of the long-period systems are single lined spectroscopic binaries with mass-ratio different from unity. The primary components in those

Astrophysics and Space Science **74** (1981) 87–96. 0004–640X/81/0741–0087$01.50.

systems are G and K giants. In order to understand the causes for the enhanced chromospheric activity of these systems we started a programme to observe a few selected RS CVn-type systems of short and long period and having a range of geometrical and physical parameters.

HR 1099 (V711 Tau) is the brightest of the RS CVn-type binaries. Bopp and Fekel (1976) found it to be a double-lined spectroscopic binary with an orbital period of $2\overset{d}{.}83782$. Earlier photometry of HR 1099 (Bopp *et al.*, 1977; Cousins, 1963; and Landis *et al.*, 1978) indicated that the system is not an eclipsing binary, but showed quasi-sinusoidal light variations with an amplitude of $\sim 0\overset{m}{.}10$. Recently HR 1099 has received considerable attention after it was found to produce variable radio emission and radio flares (Owen *et al.*, 1976; Feldman *et al.*, 1978). In this paper, we report the photoelectric observations of HR 1099 made at Kavalur and an analysis of all the published photoelectric ΔV and ΔB observations.

2. Observations

Observations of HR 1099 were made with the 34 cm cassegrain reflector telescope at Kavalur through standard *B* and *V* filters on 18 nights during the period 20 January, 1977 to 14 March, 1977. An unrefrigerated 1P21 photomultiplier, DC amplifier and strip chart recorder were used. The faint visual companion (ADS 2644B, K3V) which is 6 arc sec away from HR 1099 was included in all the observations. 10 Tau was used as the comparison star, whose light is found to be constant by earlier investigators. Nightly atmospheric extinction corrections were determined from the observations of the comparison. All the observations are corrected for atmospheric extinction and then differential magnitudes (variable star − comparison star) are determined. *UBV* standard stars were observed on several nights. The magnitude and colour transformation coefficients determined from the standard stars observations are $\mu = 1.054 \pm 0.009$ and $\epsilon = 0.037 \pm 0.005$. Using the transformation coefficients the differential magnitudes are transformed to the standard system.

The heliocentric Julian day of the observation and ΔV and ΔB values are listed in Table I. Each value of ΔV and ΔB given in Table I is the average value of five independent measurements. The mean error of a single observation estimated from the standard star observations is $\pm 0\overset{m}{.}008$.

HR 1099 is one of the few RS CVn-type close binary systems that show strong Hα emission (Bopp and Fekel, 1976). Four spectrograms of HR 1099 were obtained during October–November 1978 with the 102 cm reflector telescope at Kavalur. Spectra with a dispersion of 42 Å mm^{-1} at Hα were obtained using the cassegrain-image tube spectrograph.

3. Discussion

The heliocentric julian days of observations given in Table I are converted into orbital phases with the following ephemeris: JD(Hel.) $= 2442766.069 + 2\overset{d}{.}83782E$.

TABLE I

B and *V* observations of HR 1099

JD(Hel.)	ΔB	ΔV	JD(Hel.)	ΔB	ΔV
2443000 +			2443000 +		
169.1588	1.870	1.511	200.0972	1.894	1.535
176.1028	1.916	1.559	200.1097	1.885	1.528
176.1179	1.931	1.557	201.1306	1.856	1.522
176.1358	1.923	1.559	201.1436	1.848	1.516
176.1533	1.918	1.571	202.0852	1.941	1.585
176.1677	1.896	1.575	202.0978	1.946	1.576
177.1075	1.854	1.482	202.1119	1.939	1.564
177.1225	1.840	1.481	202.1258	1.944	1.578
177.1386	1.846	1.476	205.0942	1.944	1.569
196.0938	1.969	1.604	205.1080	1.933	1.563
196.1141	1.970	1.606	205.1227	1.927	1.549
196.1307	1.960	1.622	205.1370	1.935	1.559
196.1431	1.961	1.614	205.1479	1.917	1.550
196.1538	1.953	1.599	207.0901	1.911	1.556
196.1632	1.950	1.610	207.0973	1.905	1.555
197.0813	1.914	1.522	208.0819	1.934	1.544
197.0917	1.906	1.524	208.0960	1.908	1.539
197.1027	1.911	1.529	209.0850	1.870	1.506
197.1155	1.905	1.523	210.0795	1.951	1.587
197.1282	1.903	1.510	210.0999	1.953	1.610
197.1416	1.888	1.505	212.0945	1.884	1.512
199.0846	1.976	1.606	212.1046	1.906	1.535
199.0969	1.969	1.607	213.1040	1.992	1.632
199.1073	1.977	1.599	217.0908	1.887	1.525
200.0843	1.871	1.512	217.1050	1.876	1.526

The zero phase corresponds to conjunction with the more active component in front and the period is the orbital period determined spectroscopically by Bopp and Fekel (1976). In Figure 1, the ΔV and ΔB normal points (Table I) are plotted against orbital phase. From the light curves (Figure 1) we find that the light minimum is at 0.55 phase and the amplitude is $0^m.10 \pm 0.004$ in both *B* and *V*. The ΔV at maximum light level and minimum light level is found to be $1^m.51$ and $1^m.60$, respectively. During the interval of our observations, we noticed HR 1099 to brighten by $\sim 0^m.05$ on three occasions $JD_\odot$ 2443164.17, $JD_\odot$ 2443176.14 and $JD_\odot$ 2443177.12; the corresponding phases are 0.28, 0.50 and 0.85, respectively. Landis *et al.* (1978) earlier noticed a similar brightening of HR 1099 on one night. There seems to be no phase dependence for the occasional brightening. More recently Guinan *et al.* (1979) found a similar brightening of $0^m.06$ above normal on 30 November, 1979. They find that $H\alpha$ index on that night has increased by $0^m.03$

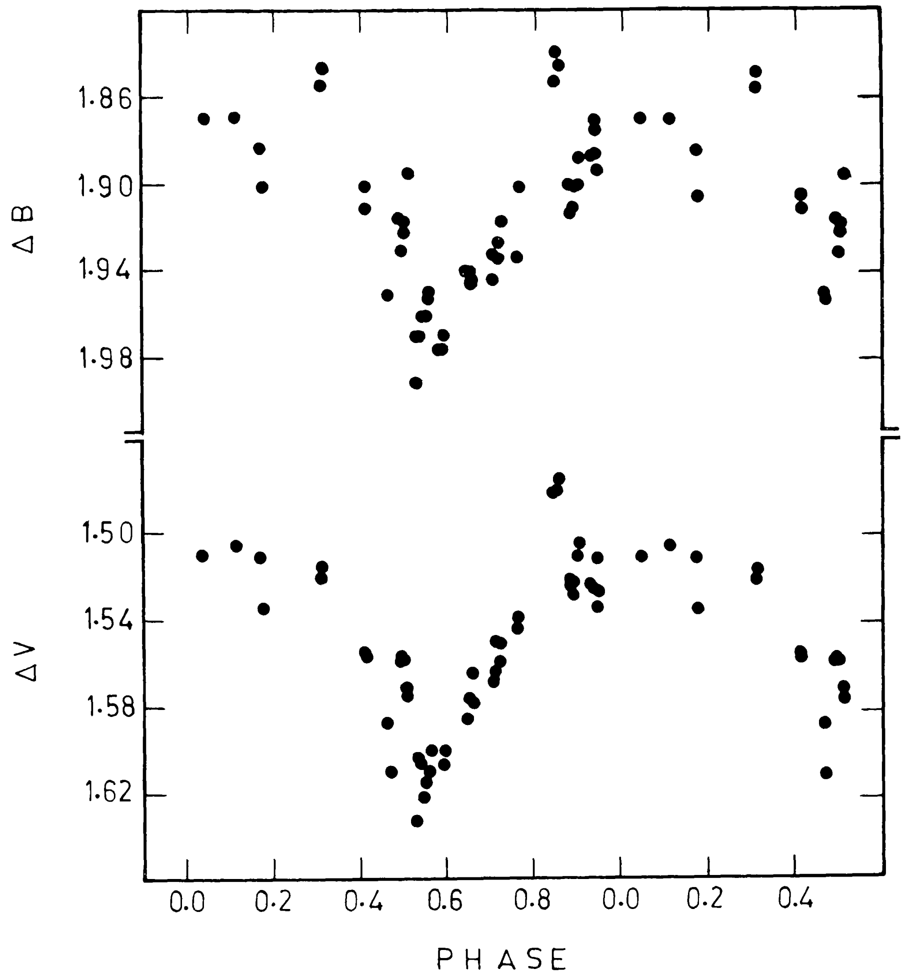

Fig. 1. Light curve of HR 1099.

above the mean. Sudden increase in brightness by a few hundredths of a magnitude and slow decay seems to be happening often in HR 1099. This occasional brightening in the optical region may indicate flare like events lasting for a few hours to less than a day.

3.1. Phases of light minimum

Landis *et al.* (1978) found that the wave minimum had migrated retrograde by 0.074 phase since 1976 and suggested a wave migration period of 13 years. Recent observations (Chambliss *et al.* (1978), Chambliss and Detterline (1979), Guinan (1979) and Raveendran *et al.* (1980)) indicated that the wave migration is towards increasing orbital phase. We analysed all the published photoelectric ΔV observations and determined amplitude and phases of minimum light and maximum light. Observations given in the papers of Bartolini *et al.* (1978) and Chambliss *et al.* (1978) were also utilized, excluding the observations which are not on the *UBV* standard system. Observations of Chambliss and Detterline

(1979), Dean (1979), Guinan *et al.* (1979) and Antonopoulou and Williams (1980) are used to estimate the phases of minimum and maximum light level of HR 1099. All phases are computed with the ephemeris mentioned above. When we plot observations made within a few orbital periods, we could distinguish variations in the amplitude and shape of the light curves. The light curves of HR 1099 were found to show simple sinusoidal light variations to quasi-sinusoidal and asymmetric light variations. Therefore, we divided all the available ΔV observations into different groups covering a few cycles of orbital period. The amplitude and phases of minimum light are determined from the graphical plots. Phases of light minimum and amplitude of the light variation determined from the truncated Fourier series, $\ell = A_0 + A_1 \cos\theta + A_2 \cos 2\theta + B_1 \sin\theta$ agree very well with those determined from the graphical plots. However, whenever the observations are few and light variations are symmetric we find that the two methods give slightly different results. The amplitude and phases of maximum and minimum light levels determined from the graphical plots are given in Table II together with the interval of observations. The ΔV values at maximum and minimum light levels are also given in Table II. In Figure 2, the phases of minimum light are plotted against Julian day. From Figure 2, it is clear that the phase minimum of HR 1099 migrated towards decreasing orbital phases during the interval JD 2442720 to JD 2443000 and from JD 2443200 there is almost a linear increase of phase minimum from 0.54 to its present value of 0.95 with a rate of ~0.0012 phase per one orbital period. In Figure 2, we have also plotted the phases of maximum light. The phases of light maximum show the same characteristic behaviour as that of phases of light minimum.

The nature of light variations of HR 1099 changed significantly from 1977 to 1979. The phase minimum migrated rapidly from 0.55 in 1977 (JD 2443200) to 0.74 during the major radio outburst in 1978 (JD 2443574) and then to 0.95 in 1979 (JD 2444194). If the light variations of HR 1099 are due to star spot activity similar to that found in BY Dra, then the migration of phase minimum (Figure 2) suggests that there is a direct migration of spotted region with a period of 6.6 years. The phases of light minimum (Table II) sometimes show to and fro behaviour suggesting that the migration is not taking place smoothly. Superimposed on the migrating wavelike distortions orbital period variation cannot be ruled out. The value of the phase minimum is found to increase almost linearly with time during the interval JD 2443181 to JD 2444196 (Figure 2); from a linear least squares solution of the residuals (O–C) in the times of minimum the period is found to be 2.841204 days compared to the spectroscopic period of 2.83782 days. This period represents fairly well the times of maximum and minimum during the interval JD 2443181 to JD 2444196. However, it is very difficult to explain such a large change in the period within a period of 1000 days. Further photometric and radial velocity observations are needed to determine accurately the orbital period and the period of migrating wave.

TABLE II

Phases of light minimum and maximum of HR 1099

$JD_{\odot}$	Mean JD	Phase minimum	ΔV minimum	Phase maximum	ΔV maximum	Amplitude m	Reference
2430000+	2400000+						
8026–8059	38043	0.654	1.62	0.125		0.108	1
2440000+							
2720–2776	42748	0.640	1.62	0.21	1.49	0.135	2
2750–2790	42770	0.615	1.60	0.195	1.49	0.115	2
2771–2818	42795	0.585	1.60	0.19	1.47	0.129	2
2792–2818	42805	0.57	1.59	0.185	1.47	0.125	2
2821–2836	42829	0.555	1.57	0.025	1.49	0.084	2
2821–2849	42835	0.585	1.58	0.08	1.50	0.084	2
3041–3070	43055	0.57	1.62	0.98	1.50	0.116	3
3051–3070	43060	0.57	1.61	0.00	1.49	0.07	3
3063–3130	43096	0.59	1.62	0.06	1.50	0.116	3
3177–3186	43181	0.545	1.62	0.055	1.50	0.12	3
3176–3217	43197	0.55	1.60	0.065	1.51	0.096	This paper
3195–3214	43203	0.54	1.60	0.12	1.50	0.10	This paper, 3
3374–3435	43404	0.60	1.61	0.125	1.50	0.107	4
3414–3436	43425	0.71	1.61	0.19	1.52	0.082	4
3417–3540	43479	0.68				0.075	5
3466–3551	43508	0.68	1.59	0.17	1.52	0.066	4
3484–3540	43512	0.69	1.59	0.195	1.51	0.082	4
3564–3584	43574	0.74	1.59	0.27	1.52	0.072	6
3793–3809	43801	0.895		0.32		0.086	7
3836–3860	43848	0.89				0.206	8
3907–3952	43930	0.895	1.63	0.355	1.42	0.208	9
4176–4211	44194	0.95				0.13	5, 10

References: (1) Cousins (1963); (2) Bopp *et al.* (1977); (3) Landis *et al.* (1978); (4) Bartolini *et al.* (1978); (5) Guinan *et al.* (1979); (6) Chambliss *et al.* (1978); (7) Antonopoulou and Williams (1980); (8) Dean (1979); (9) Chambliss and Detterline (1979); (10) Raveendran *et al.* (1980).

3.2. Amplitude

The visual amplitude of the light curves of HR 1099 are determined from the published photoelectric ΔV observations and are given in Table II. The mean visual amplitude excluding the observations of Chambliss and Detterline (1979) is found to be $0\overset{m}{.}10$. Recently, Antonopoulou and Williams made infrared observations of HR 1099 in J, H and K. They found an amplitude of $0\overset{m}{.}086 \pm 0.010$ in J and H. In K the amplitude is $0\overset{m}{.}064$ which is slightly smaller than that found in J and H. The amplitude of light variations seems to be independent of wavelength. The visual amplitudes determined from the ΔV observations at different epochs are plotted against Julian days in Figure 3. The amplitude is found to vary from $0\overset{m}{.}07$ to $0\overset{m}{.}21$. Small variations in amplitude of the order $0\overset{m}{.}04$ around the mean value are noticed. Recently, Chambliss and Detterline (1979) reported an increase in the light amplitude. An amplitude of $0\overset{m}{.}21$ in the light variation of HR 1099 is the largest so far observed. Recently Dean (1979)

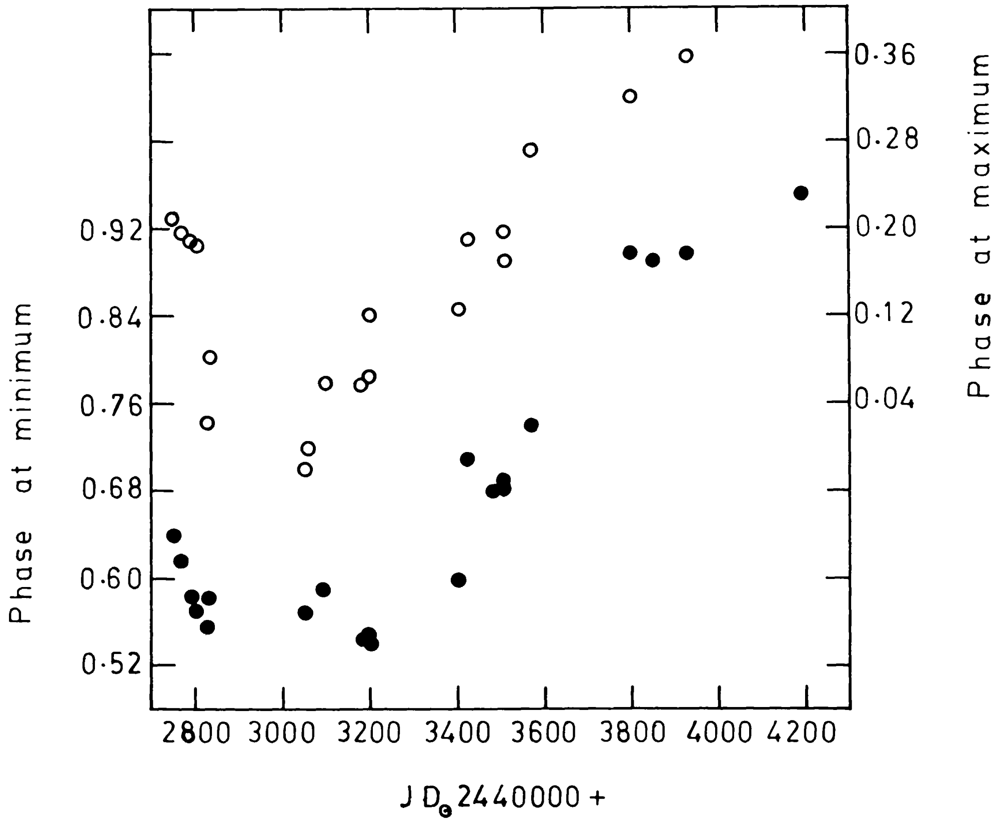

Fig. 2. Phases of minimum (filled circles) and maximum (open circles) of HR 1099 plotted against Julian Day.

reported DDO observations of HR 1099. We determined the amplitude of light variations from the DDO observations of Dean (1979) and found them to be $0^m.206$, $0^m.201$, $0^m.185$, $0^m.192$ and $0^m.171$ at 4800 Å, 4500 Å, 4200 Å, 4100 Å and 3800 Å, respectively. The gap between the DDO observations of Dean (1979) and *JHK* photometry of Antonopoulou and Williams (1980) is 27 days. Major

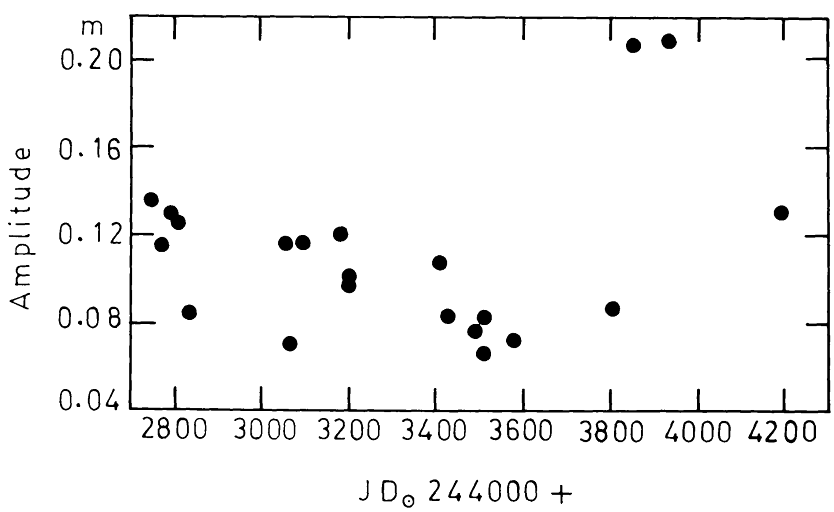

Fig. 3. Visual amplitudes plotted against Julian Day.

changes in the light variations of HR 1099 seem to have occurred just before the time of DDO observations (JD 2443836) of Dean (1979) and the system remained in that mode up to JD 2443952 (Chambliss and Detterline, 1979). For more than 116 days the amplitude of the light variations of HR 1099 is found to be $0^{m}.21$. From the observations of Chambliss and Detterline (1979) we find that the brightness of HR 1099 at maximum light has increased by $0^{m}.08$ from the mean maximum light value. Increase in the brightness at maximum appears to be related to the increase in light amplitude. The ΔV observations of HR 1099 by Cousins (1963) indicate that the system was brighter in 1963 by about $0^{m}.08$ compared to the present mean ΔV values at maximum and minimum light. Guinan *et al.* (1979) also found an increase in brightness by $0^{m}.05$ at maximum light. Rapid migration of the phases of light minimum, increase in the light amplitude, and increase in brightness at maximum light suggest that the spotted regions and regions of chromospheric activity has changed significantly.

3.3. Hα EMISSION

The four Hα emission profiles of HR 1099 determined from the image tube spectra obtained at Kavalur are shown in Figure 4. The equivalent widths are found to be 1.26 Å, 2.60 Å, 1.65 Å and 1.31 Å; the corresponding dates of observations are JD 2443795.35, JD 2443827.24, JD 2443829.32 and JD 2443830.25 respectively. On the night of 14 November, 1978 (JD 2443827.24), there was a significant increase in the Hα equivalent width and the profile changed considerably (Figure 4). The equivalent width of Hα emission in HR 1099 is known to vary from night to night (Bopp, 1979). The Hα emission equivalent width during the quiet period is of the order of 0.5–1.0 Å (Bopp and Talcott, 1978). During the radio flares strong enhancement in the Hα emission was noticed by earlier investigators (Weiler *et al.*, 1978; Bopp and Talcott, 1978; Furenlid and Young, 1978; Hearnshaw, 1978). During the major radio flare of February 1978, a peak Hα emission equivalent width of ~ 3 Å was observed by Popper (1978) and Fraquelli (1978). From our observations (Figure 4) we find change in the intensity and profile and the equivalent width of Hα (2.6 Å) has enhanced significantly on JD 2443827.24; and two days later the Hα equivalent is found to be 1.65 Å. We conclude that a major outburst of HR 1099 occurred on 14 November, 1978, which was comparable to that of February 1978 (Feldman *et al.*, 1978). The shape of the Hα profile on 14 November, 1978 (Figure 4), was found to be similar to those obtained during 1976 and 1978 radio flares (Fraquelli, 1978). Photometric observations of HR 1099 prior to 14 November, 1978 (Antonopoulou and Williams, 1980) and after 14 November, 1978 (Dean, 1979; Chambliss and Detterline, 1979) suggest that the 14 November, 1978, outburst of HR 1099 may have been responsible for the increase in light amplitude, and brightness change at light maximum. The outbursts of HR 1099 in February 1978, (Feldman *et al.*, 1978), November 1978 (this paper) and July 1979 (Feldman *et al.*, 1979) seem to have been responsible for the rapid wave migration and changes in

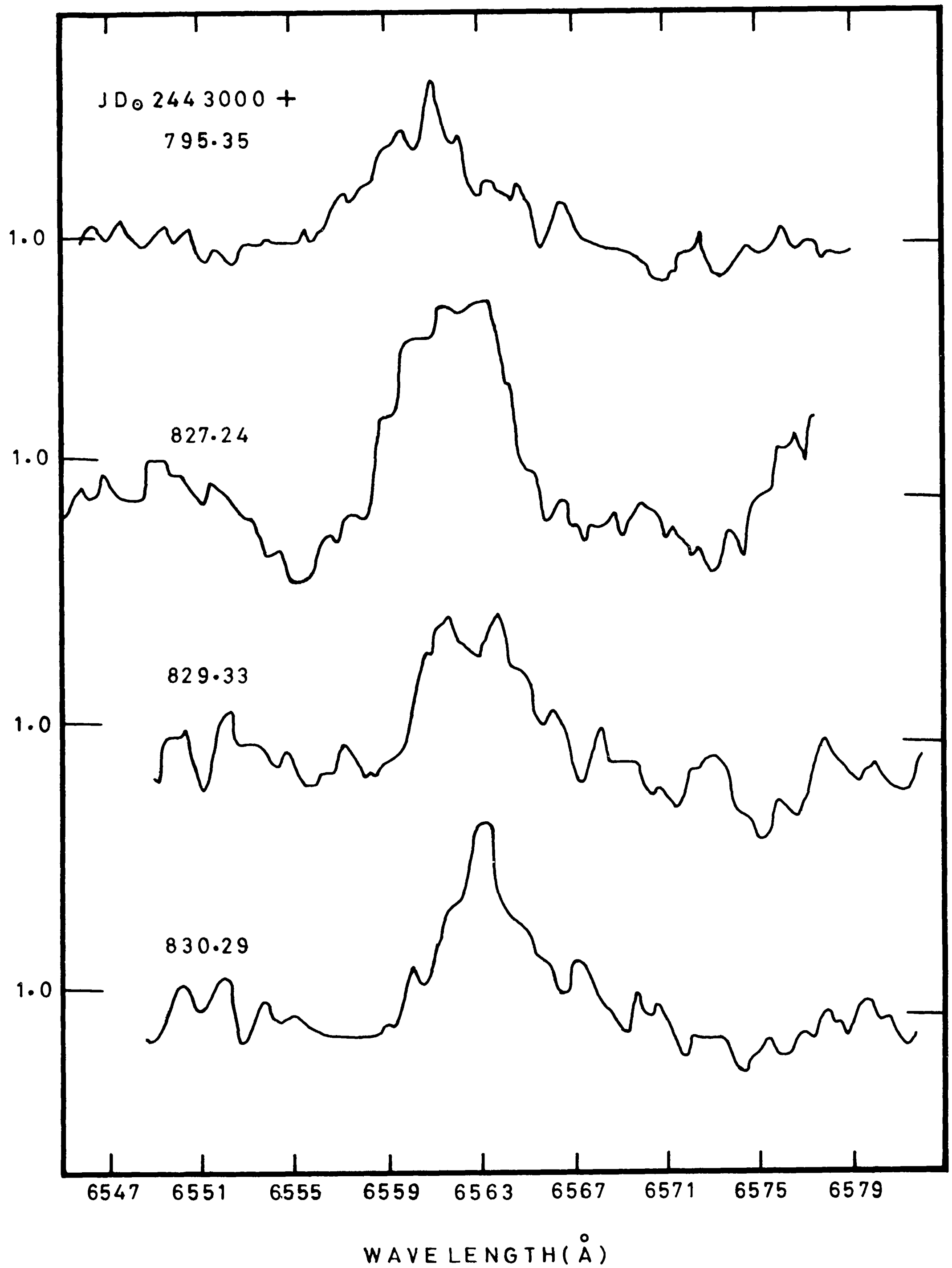

Fig. 4. Hα profiles of HR 1099.

the nature of light variations. If we assume that the light variations are caused by extensive star spot activity on the surface of the active component, then the outbursts and changes in the light curves indicate that the spotted regions have changed significantly both in intensity and scale. Ultra violet observations (Lα and Mg II) of Weiler (1978) indicate that HR 1099 possess an extremely active chromosphere. Ultraviolet observations suggest chromospheric activity in the form of plage like phenomena associated with the more active component. Rapid migration of the light minimum and changes in the amplitude and shape of the light curves may be associated with the changes in chromospheric activity in the form of plages and dark spots on the surface of the active component.

Further spectroscopic and photometric observations of HR 1099 will be useful to determine the orbital period and migration period accurately and to understand the star spot phenomenon.

Analysis of the photoelectric observations made at Kavalur during the period October 1979 to March 1980 is in progress.

Acknowledgement

We are grateful to Prof. M. K. V. Bappu for his encouragement.

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