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ASTRONOMY AND ASTROPHYSICS

Variability of classical T Tauri stars

Its relation to the accretion process

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Abstract. We present the analysis of a UBV(RI)$_c$ photometric monitoring program carried out from July 1988 to August 1992 on a sample of 13 classical T Tauri stars and 2 suspected classical T Tauri stars.

We detected optical irregular variability with an amplitude larger than 0.1 mag in the V band in 8 stars. For 5 of them most of the variability can be attributed to hot spots, for one, to cool spots and for two of them, there is no clear mechanism; nevertheless, other phenomena must explain the short term (hours – days) and long term (years) variations superimposed. For some objects an anomalous behaviour at the shorter wavelengths (U band) is detected.

From the comparison between the amplitude of the optical variability due to hot spots and the equivalent width of the H_α emission a correlation between them is suggested. Assuming that the H_α emission is related to the accretion process, this correlation supports the idea that we are observing the hot spots where the material from the accretion disks falls onto the star.

Key words: stars: formation – stars: pre-main sequence – accretion disks – star spots

1. Introduction

T Tauri stars (TTSs) are young, low mass stars ($M \leq 2\,M_\odot$) still contracting towards the main sequence. This class of variable stars was first defined on the basis of their peculiar spectra and irregular optical variability (Joy 1945, Herbig 1962). Later works have shown different behaviours for the optical variability, related to the lack or presence of periodicity and the change of the amplitude with the wavelength. These characteristics point to various mechanisms acting at possibly different evolutionary stages of the star and its close environment.

TTSs are divided into two sub-classes: classical T Tauri stars (CTTSs) and weak line T Tauri stars (WTTSs). The CTTSs, the first discovered, are characterized by a strong H_α emission line (≥ 10 Å) and large infrared and ultraviolet excesses, while the WTTSs show weak H_α emission, small infrared and ultraviolet excesses but significant X-ray emission. Most of the features that characterize each subclass suggest that accretion disks surround CTTSs whereas they must have almost disappeared (at least their inner parts) in WTTSs (see, e.g., Bertout 1989, Appenzeller & Mundt 1989). From these works the underlying stars seemed to be quite similar: their age, photospheric luminosity, mass, rotational velocities and x-ray fluxes showed no appreciable differences and cool spots were found in both subclasses (Edwards et al. 1989). Nevertheless, more recent studies have found important differences among the underlying stars:

i) Bouvier et al. (1993a,b) concluded, from a photometric monitoring of 20 TTSs, that there is a bimodal distribution of rotational velocities, with the CTTSs being the slower rotators (with a mean rotational period of 7.6 ± 2.1 days) and the WTTSs the rapider rotators (with a mean rotational period of 4.1 ± 1.7 days). Edwards et al. (1993) found a similar bimodal distribution for another sample of pre-main sequence stars. This bimodal distribution has been attributed to the braking of the star by the accretion disk through a mechanism similar to that proposed by Ghosh and Lamb (1979a,b) for neutron stars.

ii) A careful revision of the rotational periods estimated for CTTSs has shown that only one fourth of them have well defined periods (Gahm et al. 1993).

iii) Cool spots, largely considered the main cause of variability of TTS, are found both in WTTSs and CTTSs but, to our knowledge, hot spots have been found in CTTSs only (10 cases up to now, see Sect. 3.3). The hot spot apparently associated with a WTTS (TAP 57NW) is explained as an artifact due to the presence of an infrared companion (Bouvier et al. 1993a).

These three characteristics seem to be closely related to the accretion process.

Cool spots are considered large scale analogues of the solar spots, but the origin of the hot spots is still under discussion. Their presence cannot be inferred directly from an accretion theory that involves no other forces than gravity and the centrifugal force because, such a case, accretion should give rise

Send offprint requests to: M. Fernández to a hot equatorial region (the boundary layer). This layer is not able to reproduce the observed variability, since the time scales related with instabilities in the accretion process are of the order of hours, shorter than the time scales observed (a few days). An alternative could be a magnetosphere which would deflect the accreting material to higher latitudes, generating isolated or annular regions which, in case of misalignment between the rotational and magnetic axis, could reproduce the variability (Uchida & Shibata 1984, 1985; Königl 1991). However the matter is still open.

In order to study the optical continuum variability of CTTSs and its relation to other processes taking place in these stars (accretion and mass loss), we chose a sample of 13 CTTSs and 2 suspected CTTSs with different H_α equivalent widths (see Table 1). The emission of this line being an indicator of material in the surroundings of the star. We carried out a UBV(RI)$_c$ photometric monitoring program, from July 1988 to August 1992, devoted to the study of variability with time scales of days, weeks, months and years. The observations are described in a separate paper where the photometric UBV(RI)$_c$ measurements are tabulated (Fernández 1995).

We detected optical variability with an amplitude larger than 0.1 mag in the V band in 8 stars. Comparing the observational results for these variable stars with the stellar spot models, we conclude that for 5 stars hot spots reproduce the variability, for one, cool spots and for two of them there is no clear mechanism. Then we discuss different aspects of the variability: the superposition of different time scale variations, the anomalous behaviour found for some objects in the U band and the irregular nature of the variability. Finally, the possible physical environment of these stars and of the *constant* stars is discussed.

Table 1. The stars of our sample ordered by increasing right ascension. In column 1 their number in the Herbig and Bell (1988) catalog is indicated. Spectral types and classifications are taken from Herbig & Bell (1988); the H_α equivalent widths, W(H_α), are taken from: $^{(1)}$ Fernández et al. (1995) or $^{(2)}$ Herbig & Bell (1988).

HBC No.	Object	Sp. type	Type	W(H_α) (Å)
10	LkH$_\alpha$264	K5	CTTS	90$^{(1)}$
11	LkH$_\alpha$325	K7,M0	CTTS	20$^{(1)}$
20	LkH$_\alpha$330	G3:	CTTS	20$^{(2)}$
254	AS 205	K5	CTTS	155$^{(2)}$
270	V1121 Oph	K5	CTTS	103$^{(1)}$
292	AS 353A	cont	CTTS	150$^{(2)}$
293	LH$_\alpha$483-41	F0:e		12$^{(1)}$
295	LkH$_\alpha$228	K1,2	CTTS	15$^{(1)}$
301	LkH$_\alpha$191	K0,3	CTTS	22$^{(2)}$
302	V1331 Cyg	cont	CTTS	59$^{(1)}$
303	LkH$_\alpha$321	G:eq	CTTS	26$^{(2)}$
305	LkH$_\alpha$324	A,F		21$^{(1)}$
308	LkH$_\alpha$349	F6,8eq	CTTS	10$^{(2)}$
315	DI Cep	G8	CTTS	95$^{(2)}$
318	BM And	K5	CTTS	20$^{(1)}$

Table 2. Brightness in the V band and colour indices of the comparison stars. The prefix *Cx* to the T Tauri stars denote the best comparison star chosen among a previous sample of selected comparison stars in the field.

Star	V	(B-V)	(U-B)	(V-R)	(V-I)
C4 LkH$_\alpha$264	9.90	0.76	0.32	0.36	0.72
C3 LkH$_\alpha$330	11.62	0.73	0.22	0.39	0.82
C3 LkH$_\alpha$325	11.06	0.73	0.14	0.37	0.74
C2 AS 205	12.33	0.71	0.46	0.44	0.90
C1 V1121 Oph	12.18	0.65	-0.22	0.44	0.92
C2 AS 353	11.47	0.77	0.30	0.40	0.79
C1 LH$_\alpha$483-41	12.40	0.59	0.07	0.36	0.70
C2 LkH$_\alpha$228	11.79	0.89	0.56	0.46	0.90
C1 LkH$_\alpha$191	12.51	0.80	0.31	0.44	0.87
C2 V1331 Cyg	12.44	0.83	0.42	0.42	0.82
C1 LkH$_\alpha$321	11.60	0.55	0.04	0.30	0.59
C4 LkH$_\alpha$324	12.48	0.68	0.15	0.33	0.66
C5 LkH$_\alpha$349	11.08	1.49	1.52	0.82	1.62
C4 DI Cep	10.76	0.67	0.17	0.34	0.70
C4 BM And	11.79	1.14	0.82	0.58	1.16

2. Observational results

The observational procedure and data reduction process are described by Fernández (1995). The error of the individual measurements are around 0.03 mag for the BV(RI)$_c$ bands and around 0.05 mag for the U band. The sample of stars is shown in Table 1. In this section we present first the results for the *constant* objects, i.e., those with an amplitude lower than 0.1 mag in the V band, and secondly the variable objects, ordered by increasing amplitude in the V band. All figures represent the difference between the object and a close comparison star, selected by its constant brightness and its (B-V) index similar to that of the object. The absolute brightness in the V band of the comparison stars and their colour indices are indicated in Table 2. Their coordinates are given in Fernández (1995) and finding charts can be provided by the authors after request.

2.1. Constant or almost constant objects

For each *constant* object we present a figure with the V band light curve and a table with the average brightness in the V band and colour indices at all the observing runs. The colour indices are compared with the standard values for the spectral type of each star (indicated in Table 1).

2.1.1. LkH$_\alpha$228 (HBC 295)

Its brightness is constant, with a dispersion of 0.03 mag in the V band at each observing run and variations of less than 0.06 mag between different observing runs (see Fig. 1 and Table 3). Nevertheless, the (B-V) colour index shows a dispersion of 0.07 mag that seems to be real. In August 1991 there was an offset between the Romeo and Juliet measurements due to the different positions, on the nebula surrounding the object, where both photometers measured the background sky.

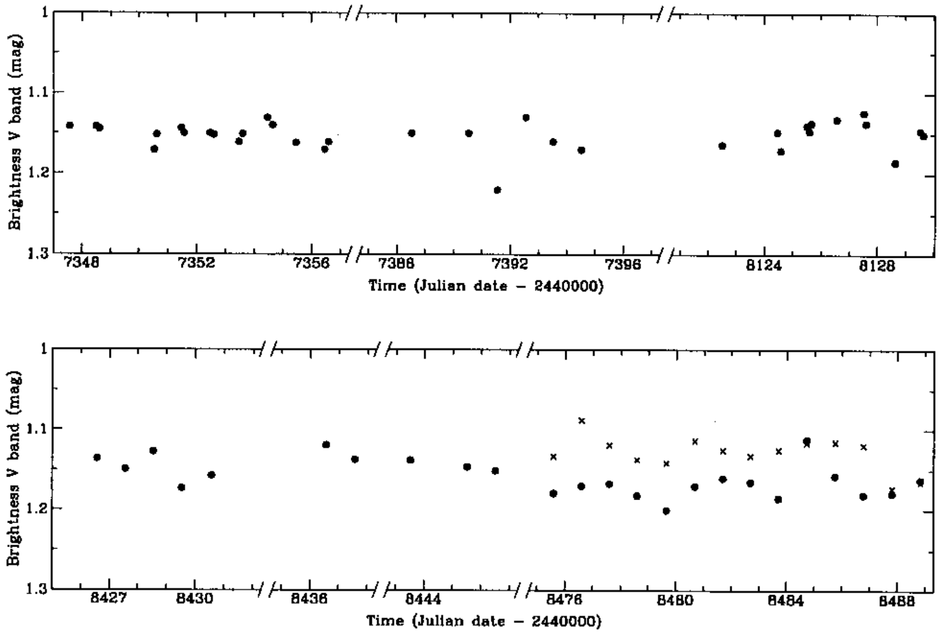

Fig. 1. Photometric observations of LkH$_\alpha$228 from July 1988 to August 1991. The difference in brightness between the star and its comparison star is plotted. For those periods where simultaneous observations were made with the two photometers Romeo and Juliet, the symbols • and * correspond to each of them, respectively (see Fernández 1995). This convention is used throughout the paper.

Table 3. Average values of the photometric observations of LkH$_\alpha$228. The brightness in the V band and the colour indices are given in magnitudes. R and J denote the Romeo and Juliet photometers, respectively. This data presentation is used from Table 3 to Table 9.

Date	V	(B-V)	(U-B)	(V-R)	(V-I)
July 1988	12.93	0.83	0.27		
August 1988	12.96	0.84	0.29		
August 1990	12.94	0.80	0.28	0.51	0.98
Jun.Jul.1991	12.96	0.85	0.28	0.51	1.00
Aug.1991 (R)	12.91	0.89	0.32	0.48	0.97
Aug.1991 (J)	12.91	0.88	0.34	0.48	0.98
Sept. 1991	12.97	0.83	0.29	0.50	0.98

The average value we found for the brightness in the V band agrees with that reported by Cohen and Kuhi (1979) for the date 29 July 1974 (13.2:).

The colour indices of LkH$_\alpha$228 correspond to those of a K1,2 V star (Buser & Kurucz 1992), however the (U-B) index agrees with that of a hotter star.

2.1.2. LkH$_\alpha$191 (HBC 301)

This star has a constant brightness. Its location in the North America Nebula (NGC 7000) increases the observational errors, due to the difficulty of subtracting an appropriate background (see Fig. 2 and Table 4).

Cohen and Kuhi (1979) reported a brightness of 12.8: in the V band for the dates 27 and 28 July 1974, which agrees with the average value we found.

Comparing the average values of its colour indices with those assigned by Buser and Kurucz (1992) to a K0,3V star, an excess E_{B-V}=0.29 mag is found. Taking into account this reddening, the (V-I) and (U-B) indices show average values 0.4 and 0.1 mag, respectively, higher than expected for a K0,3 star.

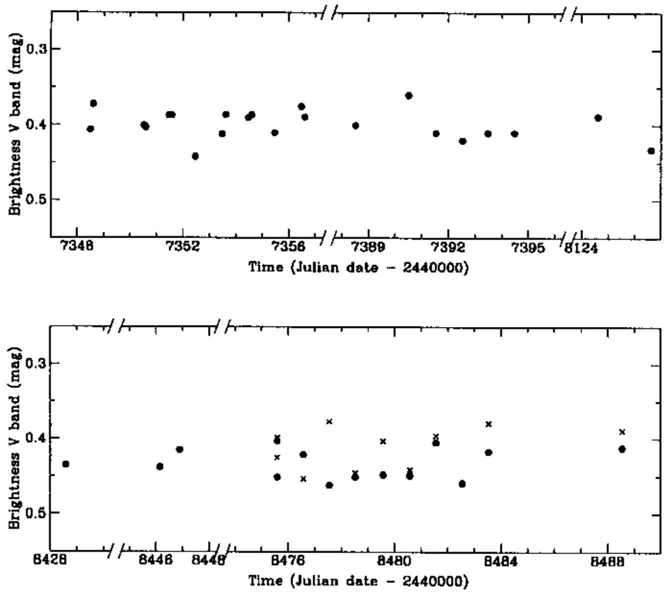

Fig. 2. Photometric observations of LkH$_\alpha$191 from July 1988 to August 1991.

2.1.3. LH$_\alpha$483-41 (HBC 293)

Our observations suggest that it has a constant brightness (Fig. 3 and Table 5), in contrast with the results of Herbst et al. (1982), who found variations in the V band between 11.56 and 11.82 mag.

Comparing the average values of its colour indices with those assigned by Johnson (1966) to a F0 star an excess E_{B-V} = 0.5 mag is found. Taking this reddening into account, the excess for the (V-I) colour index is 0.6 mag.

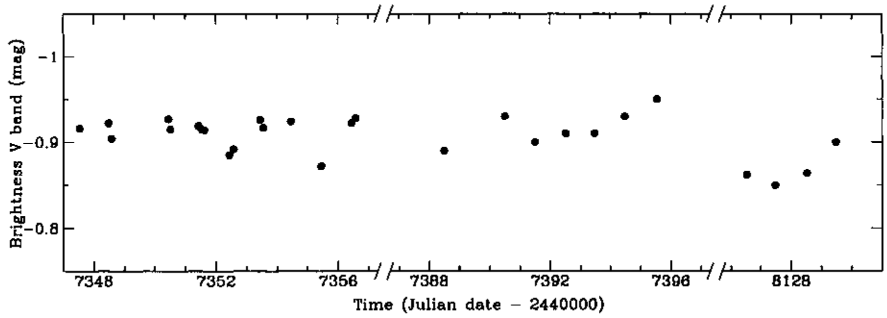

Fig. 3. Photometric observations of LH_α483-41 in July and August 1988 and August 1990.

Table 4. Average values of the photometric observations of LkH_α191.

Date	V	(B-V)	(U-B)	(V-R)	(V-I)
July 1988	12.92	1.11	0.59		
August 1988	12.96	1.14	0.64		
August 1990	12.93	1.07	0.63	0.69	1.06
Jun.Jul.1991	12.99	1.14	0.68	0.71	1.42
Aug.1991 (R)	12.89	1.17	0.65	0.68	1.44
Aug.1991 (J)	12.90	1.15	0.62	0.70	1.43

Table 5. Average values of the photometric observations of LH_α483-41.

Date	V	(B-V)	(U-B)	(V-R)	(V-I)
July 1988	11.50	0.83	0.29		
August 1988	11.56	0.83	0.29		
August 1990	11.53	0.84	0.33	0.56	1.15

Table 6. Average values of the photometric observations of LkH_α321.

Date	V	(B-V)	(U-B)	(V-R)	(V-I)
August 1990	12.36	1.16	0.33	0.78	1.47
Jun.Jul.1991	12.36	1.19	0.43	0.78	1.56
Aug.1991 (R)	12.35	1.19	0.48	0.76	1.54
Aug.1991 (J)	12.36	1.18	0.51	0.75	1.50

2.1.4. LkH_α321 (HBC 303)

Shevchenko et al. (1991) detected in August 1988 a weakening of 0.1 in the V band for this star, followed by an increase of 0.2 mag. Before this change, the dispersion of the brightness of the star was less than 0.05 mag, but after that the dispersion increased slightly.

The average brightness we have measured in the V band for this star agrees with the value found by Shevchenko et al. (1991) at those dates of constant brightness (see Fig. 4 and Table 6). We have to point out that during our observations the (U-B) colour index changed from 0.33 to 0.51 mag.

LkH_α321 has a moderate UV excess for its spectral type (Chavarría-K. & Lara 1981) and an excess in the intermediate infrared (Chavarría-K. 1981). Comparing our measured average values of its colour indices with those assigned by Buser and Kurucz (1992) to a G8 star, an excess E_{B-V} = 0.5 mag is found. Taking this reddening into account the (V-I) colour index excess is 0.6 mag.

Table 7. Average values of the photometric observations of LkH_α324.

Date	V	(B-V)	(U-B)	(V-R)	(V-I)
Jun.Jul.1991	12.64	1.08	0.54	0.72	1.50
Aug.1991 (R)	12.60	1.08	0.55	0.75	1.51
Aug.1991 (J)	12.62	1.07	0.56	0.71	1.48
Sept. 1991	12.63	1.09	0.52	0.72	1.50
Nov. 1991	12.63	1.11	0.58	0.73	1.49
Aug.1992 (R)	12.63	1.11		0.71	1.47
Aug.1992 (J)	12.64	1.12	0.57	0.72	1.49

2.1.5. LkH_α324 (HBC 305)

LkH_α324 has a controversial spectral type. Chavarría-K. et al. (1983) discussed the types given by different authors between F7 and B and suggested that the properties of the star vary between a hot star with a pure absorption spectrum and those of a relative cool T Tauri-like object.

Our observations show a constant brightness (see Fig. 5 and Table 7). There is a small offset between the Romeo and Juliet measurements due to the reason indicated for LkH_α228.

The constancy of brightness that we have found is in agreement with the results obtained by Shevchenko et al. (1991) during 1987 and 1988. Nevertheless, other authors have obtained very different values. Cohen and Kuhi (1979) found a value of 13.4 mag in July 1974, Chavarría-K. (1981) found a value of 11.50 ± 0.15 mag in 1979 and Kolotilov (1986) observed variations from 12.64 to 12.83 mag during 1983 and 1985.

Comparing the average values of the colour indices with those assigned by Johnson (1966) to a F5, an excess E_{B-V} = 0.7 mag is found, similar to that obtained by Chavarría-K. et al. (1983). Taking into account this reddening the (V-I) colour index is still 0.8 mag larger than expected.

2.1.6. LkH_α330 (HBC 20)

Our observations present a dispersion larger than what would be expected from the observational errors if it had constant brightness. Nevertheless, the lack of good comparison stars makes the analysis difficult (see Fig. 6 and Table 8). One must take into account that it is a very red object and its (B-V) colour index is in the border of the range defined by the standard stars used for the calibration. The average values that we obtained in the V band are quite different from that of Strom et al. (1974), 10.97 mag, while the colour indices are very similar.

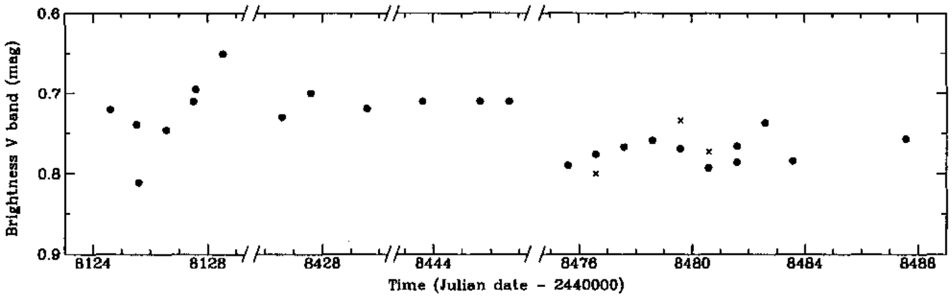

Fig. 4. Photometric observations of LkH$_\alpha$321 in August 1990 and June, July and August 1991.

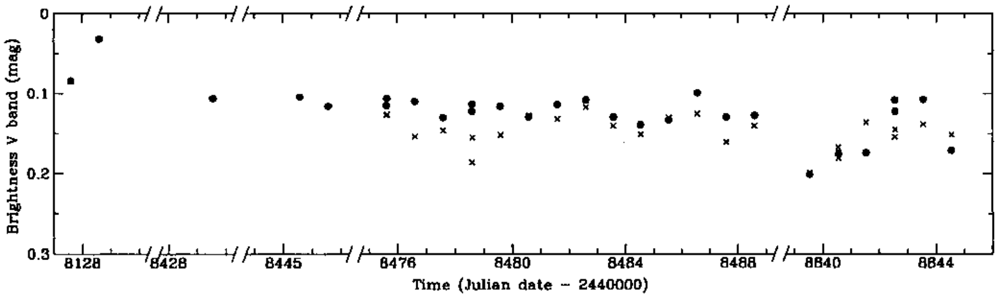

Fig. 5. Photometric observations of LkH$_\alpha$324 in August 1990, June, July and August 1991 and August 1992.

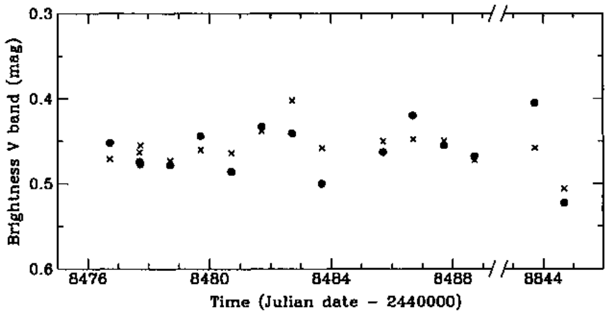

Fig. 6. Photometric observations of LkH$_\alpha$330 in August 1991 and 1992.

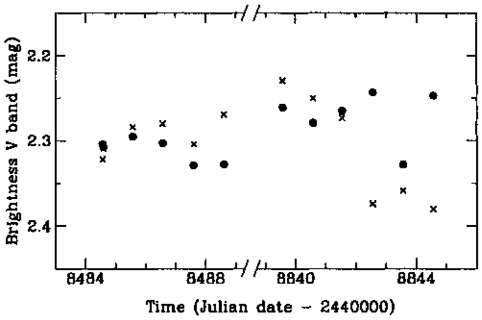

Fig. 7. Photometric observations of LkH$_\alpha$349 in August 1991 and 1992.

Table 8. Average values of the photometric observations of LkH$_\alpha$330.

Date	V	(B-V)	(U-B)	(V-R)	(V-I)
Aug.1991 (R)	12.07	1.26	0.77	0.83	1.69
Aug.1991 (J)	12.06	1.25	0.79	0.83	1.69
Sept. 1991	12.07	1.35	0.66	0.85	1.72
Aug.1992 (R)	12.09	1.19	0.68	0.84	1.71
Aug.1992 (J)	12.10	1.27	0.75	0.83	1.73

Comparing the average values of its colour indices with those assigned by Buser and Kurucz (1992) to a G5 star, an excess E_{B-V} = 0.6 mag is found. Taking into account this reddening, an excess of 0.8 mag is found for the (V-I) colour index.

2.1.7. LkH$_\alpha$349 (HBC 308)

LkH$_\alpha$349 seems to have two distinct photometric states at a brightness of 16.2 mag and 15.4 mag in the B band, with some outbursts reaching 14 mag (Hessman et al. 1995). This object is quite reddened, as is revealed by the comparison between its (B-V) index of 1.5 mag and that of a F6,8 star (0.53 mag, Buser & Kurucz 1992). This value is outside the range defined by the standard stars and for this reason the errors in the BV$(RI)_c$ bands exceed 0.03 mag, and are even larger for the U band.

As shown in Fig. 7 the brightness of the object was constant during the observations until the last nights in August 1992, when it decreased 0.1 mag in the BV$(RI)_c$. Our average value for the brightness in the V band is similar to that of Dibai (1969), 13.3 mag, but a little different from the value reported by Cohen and Kuhi (1979), 13.0 mag.

Taking the E_{B-V} into account, the (V-I) colour index is 1.2 mag larger than expected for a F8 star.

2.2. *Variable objects*

For the variable objects two figures are presented for almost all the observational runs: the V band light curve and the UB(RI)$_c$ bands measurements against the value in the V band. The latter representation was chosen in order to see the different slopes,

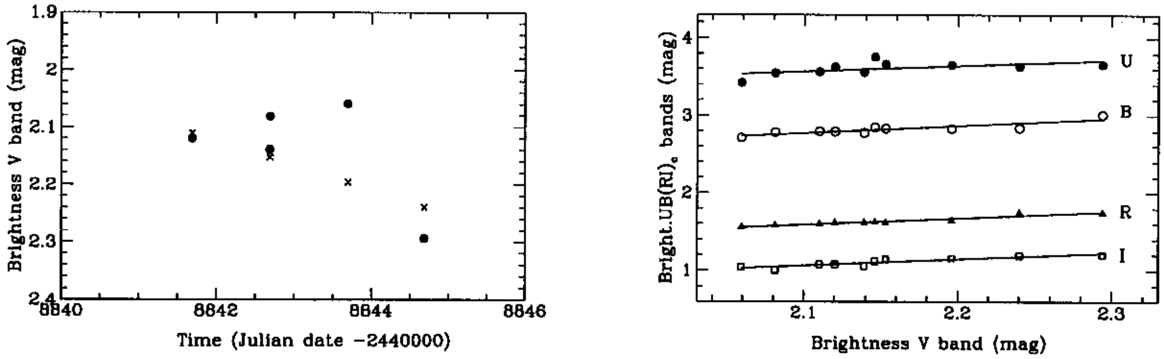

Fig. 8. Photometric observations of LkH$_\alpha$325 in August 1992.

Table 9. Average values from the photometric observations of LkH$_\alpha$349.

Date	V	(B-V)	(U-B)	(V-R)	(V-I)
August 1991	13.37	1.54	1.54	1.04	2.12
Sept. 1991	13.41	1.53	0.96	1.05	2.12
August 1992	13.37	1.53	1.04	1.06	2.14

that is, the change of the amplitude with wavelength. Observing runs with few data are not shown, though the observational data are published (Fernández 1995).

For each star we have compared the standard colour indices for its spectral type (indicated in Table 1) with the range of variability of its colour indices, defined by their maximum and minimum values. For this comparison we have used the data of Buser and Kurucz (1992), except for V1331 Cyg, for which we have taken the data of Johnson (1966). When the range of variability lies close to the standard value, the maximum difference between the observed and standard values, if larger than 0.2 mag, is quoted.

2.2.1. LkH$_\alpha$325 (HBC 11)

It is a highly reddened star, with a (B-V) colour index of 1.4 mag, outside the range of our photometric standard stars; thus, errors in the BV(RI)$_c$ bands are larger than 0.03 mag and in the U band, larger than 0.05 mag. Since the amplitude of the variability in the V band is 0.15 mag (see Fig. 8), it is not easy to derive the amplitudes of the real variability.

2.2.2. DI Cep (HBC 315)

Optical and ultraviolet spectra show that the brightness of the emission lines varies considerably with time scales of hours and days (Bastian & Mundt 1979; Gómez de Castro & Fernández 1996).

Our photometric observations show an irregular variability with an amplitude of some tenths of magnitude (Fig. 9). The behaviour of the amplitudes with wavelength is similar in both observational runs: from the I$_c$ to the B band there is a smooth increase, but from B to U the increase is steep. During August 1991, sharp peaks of brightness lasting one day were seen superimposed onto the smooth variability. Errors are probably smaller than the average values indicated for the whole sample.

The ranges of variability of the colour indices lay close to the standard values for a G8 V star, with the (U-B) index being 0.3 mag smaller than the standard value at maximum brightness and the (V-I) index 0.3 mag larger at minimum brightness.

2.2.3. V1331 Cyg (HBC 302)

Chavarría-K. (1981) suggested that it is a star of an intermediate type between TTSs and Ae/Be Herbig stars. This "intermediate type" is also supported by the characteristics of its irregular variability (Shevchenko et al. 1991).

Our photometric observations show the irregular variations (Fig. 10). The amplitude in the V band goes from 0.17 to 0.38 mag and there is no clear trend in the behaviour of the amplitude with wavelength.

This star presents an excess E_{B-V} = 0.6 mag. Taking this reddening into account we find average excesses in the (U-B), (V-R) and (V-I) colour indices of 0.5, 0.4 and 0.8 mag, respectively.

2.2.4. V1121 Oph (HBC 270)

The amplitude of the variability increases as the wavelength decreases (see Fig. 11). During August 1991, sharp peaks of brightness lasting one day were seen superimposed onto the smooth variability. The errors of these measurements are larger than 0.03 mag due to its (B-V) index outside the range defined by the standard stars, to the high air mass (>1.4 air masses) at which it was always observed and to the lack of reasonable comparison stars.

The range of variability of the (B-V) colour index of V1121 Oph contains the standard value for a K5 V star, the (V-R) index lays close to it, the (U-B) is more than 1 mag smaller and the (V-I) index almost 0.5 mag larger.

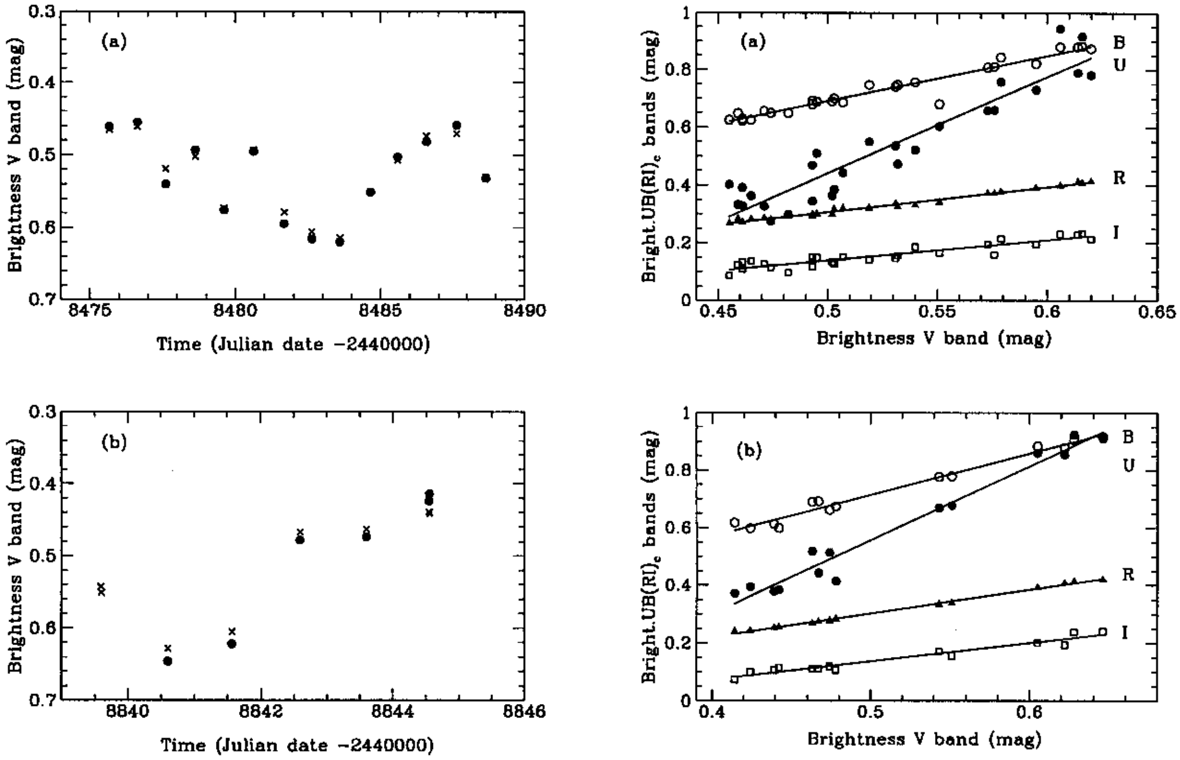

Fig. 9a and b. Photometric observations of DI Cep in **a** August 1991 and **b** August 1992.

2.2.5. LkH$_\alpha$264 (HBC 10)

Our photometric observations are presented in Fig. 12. The amplitude decreases from the B to the I band, while in the U band it presents amplitudes similar or smaller than in the B band. The observational errors are less than 0.02 mag.

Its (B-V) index is 0.4 mag smaller than expected for a K5 V star and its (U-B) index is 1.3 mag smaller. Nevertheless, the ranges of variability of the (V-R) and (V-I) indices contain the standard values.

2.2.6. AS 353 A,B (HBC 292, 685)

The observations are presented in Fig. 13. The amplitude in the V band varies between 0.34 and 0.86 mag. AS 353 A forms a binary system with a companion located 6″ from it, AS 353 B, another CTTS of spectral type K1 (Cohen & Kuhi 1979). Since the photometric observations were made with diaphragms between 21″ and 28″ of diameter, both stars were observed simultaneously. AS 353 B is about 2 or more mag fainter than AS 353 A in the V band. This makes it rather unlikely that the observed variability is due to AS 353 B, because a variation of 0.3 mag of the system would imply a variability of at least 1.3 mag in this star, making it an extremely active CTTS.

The behaviour of the amplitude with wavelength is similar to that observed in LkH$_\alpha$264: in the BV(RI)$_c$ bands it increases when the wavelength decreases, but in the U band we can find values smaller than those measured in the B band and, even, in the V band.

The behaviour of the colour indices is also similar to that of LkH$_\alpha$264. Its (B-V) index is 0.2 mag smaller than expected for a K7 V star and its (U-B) index is 1.4 mag smaller. The ranges of variability of the (V-R) and (V-I) indices contain the standard values.

AS 353 presents three types of variability superimposed with different amplitudes and time scales. There is a smooth variability with time scales of days, upon it we can see, e.g. in Fig. 13e, sharp increases of brightness in 1 or 2 days and the third type is the constant and slow decrease of the average brightness observed from July 1988 to August 1992. The annual rate for this decrease is, approximately, 0.1, 0.2, 0.2, 0.2, 0.3 mag/yr, in the UBV(RI)$_c$ bands respectively. This kind of variability, with amplitude increasing as wavelength decreases and a time scale of years, has been observed in some early type Herbig Ae/Be stars (Fernández & Eiroa 1996).

2.2.7. BM And (HBC 318)

The extraordinary amplitude of the optical variability of this star has already been reported by Walker (1980). He attributed it to variable extinction along the line of sight, since no spectroscopic variation correlated with the photometric one was detected, as he expected if the variability was due to photospheric spots.

The amplitude of the variability is one of the largest in our sample of stars (see Fig. 14). It increases as the wavelength decreases. During August 1991, sharp peaks of brightness lasting one day seem to be superimposed on the smooth variability. The (B-V) colour index is sometimes outside the range defined by

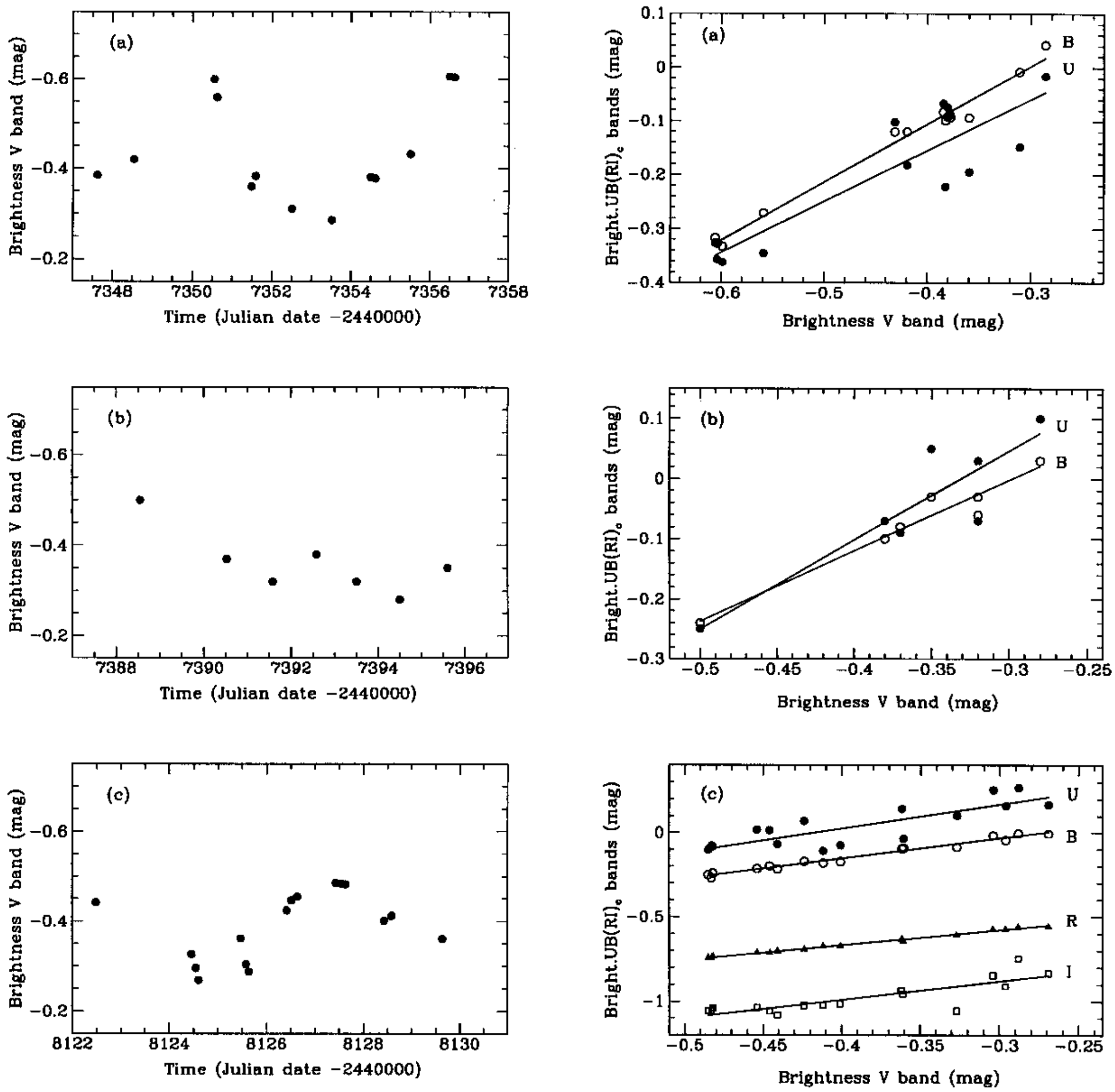

Fig. 10a–f. Photometric observations of V1331 Cyg in **a** July 1988, **b** August 1988, **c** August 1990, **d** June and July 1991, **e** August 1991 and **f** August 1992.

the standard stars, thus errors are expected to be larger than what was indicated for all the sample.

The ranges of variability of the colour indices are close to the standard values for a K5 V star, with the (U-B) index being 0.3 mag smaller than the standard value at maximum brightness and the (V-I) index 0.4 mag larger at minimum brightness.

2.2.8. AS 205, AS 205/c (HBC 254, 632)

Covino et al. (1992) observed this star in 1989 and 1990 and they reported amplitudes of 0.8 and 0.3 mag in the V band. In their observations for 1990 an uncertain period of 2.7 days was found but it was not detected in the erratic variability of 1989.

Our observations are presented in Fig. 15. These measurements correspond to the binary system that the star forms with a companion located 1″ from it, AS 205/c, 2 mag fainter than AS 205 in the V band. As was indicated for AS 353, the variability is probably related to the brighter component of the system. The errors are around 0.1 mag due to poor observing conditions (large air masses and the Moon).

Comparing with the colour indices of a K5 V star, the range of variability of (B-V) contains the standard value, (V-R) lays close to it and at minimum brightness is 0.4 mag larger than it, (U-B) is more than 1 mag smaller and (V-I) is almost 1 mag larger. This behaviour is similar to that observed for V1121 Oph.

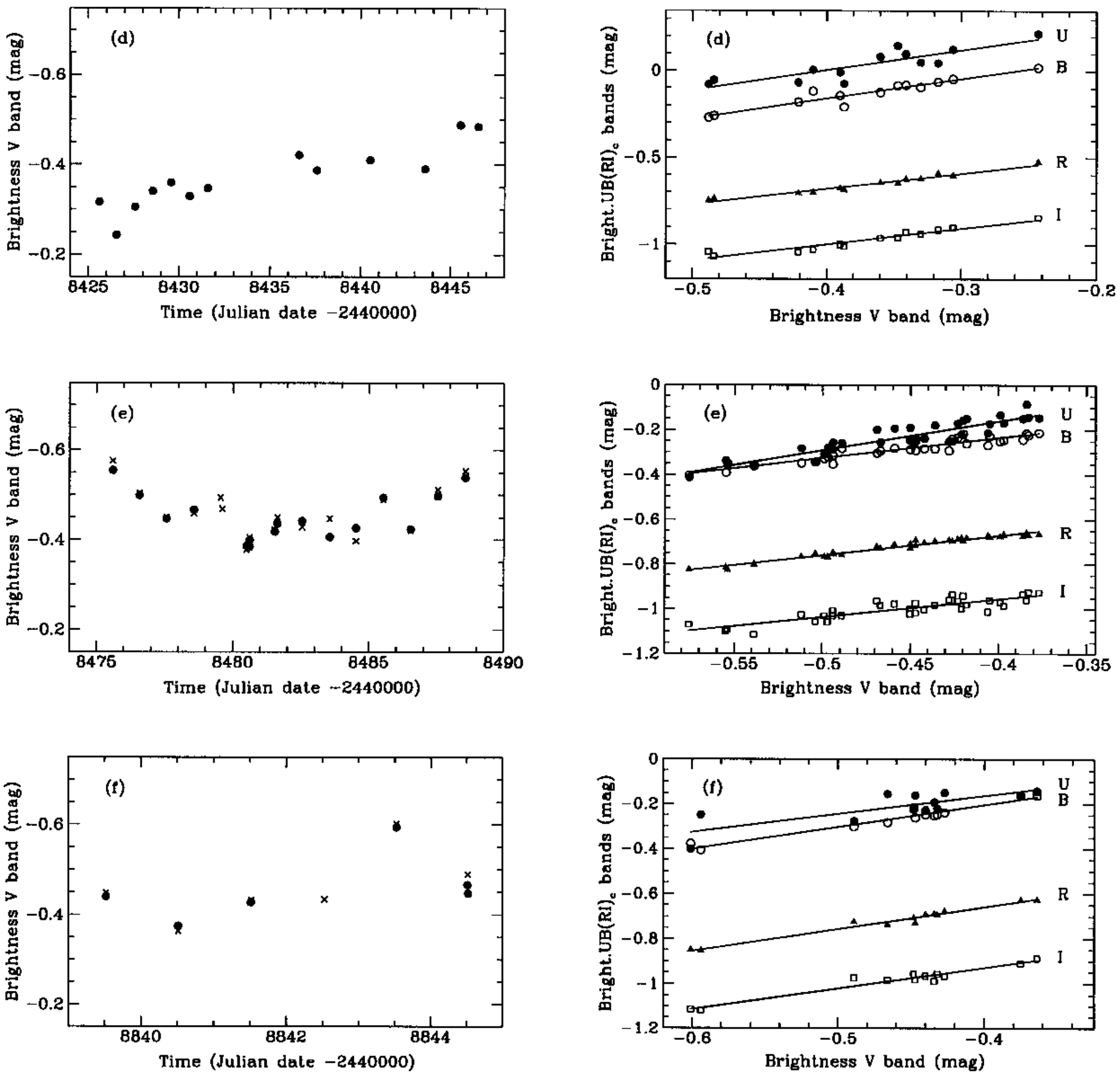

Fig. 10. (continued)

3. Discussion

3.1. The empirical models

The variability of TTSs is usually explained by empirical[1] models including cool spots, hot spots, or inhomogeneous circumstellar envelopes. We have used these models to reproduce the observed light curves in our sample and to get information about the cause of the variability.

For the star spot model we have adopted the scheme presented by Friedemann and Gürtler (1975), in which both the star and the spot are considered as black bodies [2]. This model computes the whole light curves but we have taken into account only their amplitudes because of the irregular profile of the observed light curves, i.e., we get information about the temperature and area of the spot but not about its shape or latitude. The area is a lower limit to the the maximum percentage of the visible hemisphere that the spot fills as the star rotates. It is a lower limit because *i*) we do not know the stellar inclination, *ii*) we do not take into account dark or hot regions always visible and *iii*) we may not have observed the entire light curve. For this reason the difference in temperature between the star and the spot is a maximum. For each photometric band we have computed the light curve at its central wavelength and we did not take into account its width. A linear approximation for the limb darkening is assumed. For star temperatures lower than 6500 K, the limb darkening coefficients (μ_λ) for the UBV bands have been taken from Claret and Giménez (1990), whereas they have been estimated from the solar values of Pierce and Waddell (1961)

[1] For an explanation of the choice of this term, see Safier (1995).

[2] For a detailed description of this kind of spot model, see Bouvier et al. 1993a.

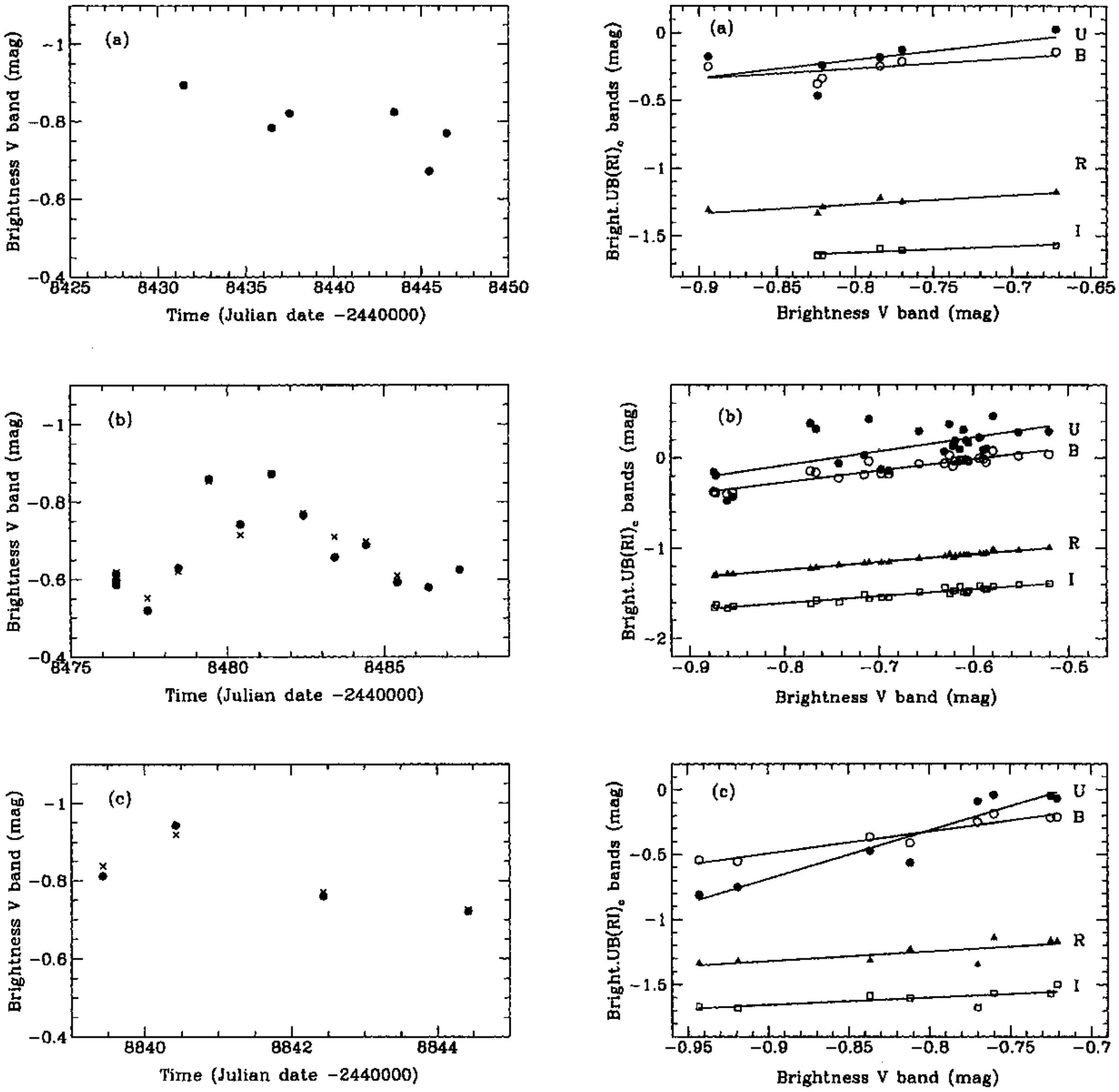

Fig. 11a–c. Photometric observations of V1221 Oph in **a** June and July 1991, **b** August 1991 and **c** August 1992.

for the R_c and I_c bands. For stars hotter than 6500 K we used the data of Díaz-Cordovés and Giménez (1995).

For the inhomogeneous circumstellar envelope we have made a simple assumption: the matter in the surroundings of the star produces an extinction that follows the mean law of interstellar reddening.

All these models predict amplitudes that increase as the wavelength of the band decreases.

In general, the luminosity of young objects in the visible wavelength range does not only come from the star photosphere, but also from material in the surroundings of the star, which produces a luminosity excess (e.g., companion stars and circumstellar disks). This excess can be accounted for in the star spot model (Vogt 1981). Red companion stars and excesses in the R and I bands reduce the R and I amplitudes of the variations because, superimposed on the enhanced continuum at these wavelengths, the variability represents a smaller amount relative to the continuum than in the case of a black body. As a consequence, the temperature of the fitted spot is larger than in the case of no red excess. On the other hand, veiling and blue companions reduce the U and B amplitudes, resulting in lower temperatures for the spots (Bouvier et al. 1993a). In order to take into account this effect, one must know the spectral distribution of the extra contribution.

The spot model provides ranges in area and temperature for the star spots. We have checked that for amplitudes one order of magnitude larger than the errors, the amplitude changes enough with wavelength in order to be able to distinguish a hot spot from a cool spot, even when they are close to the limb of the star. We have also checked that we can distinguish whether the spot is cooler or hotter than the photosphere with fragments of the light curves which do not include the maximum and/or minimum of

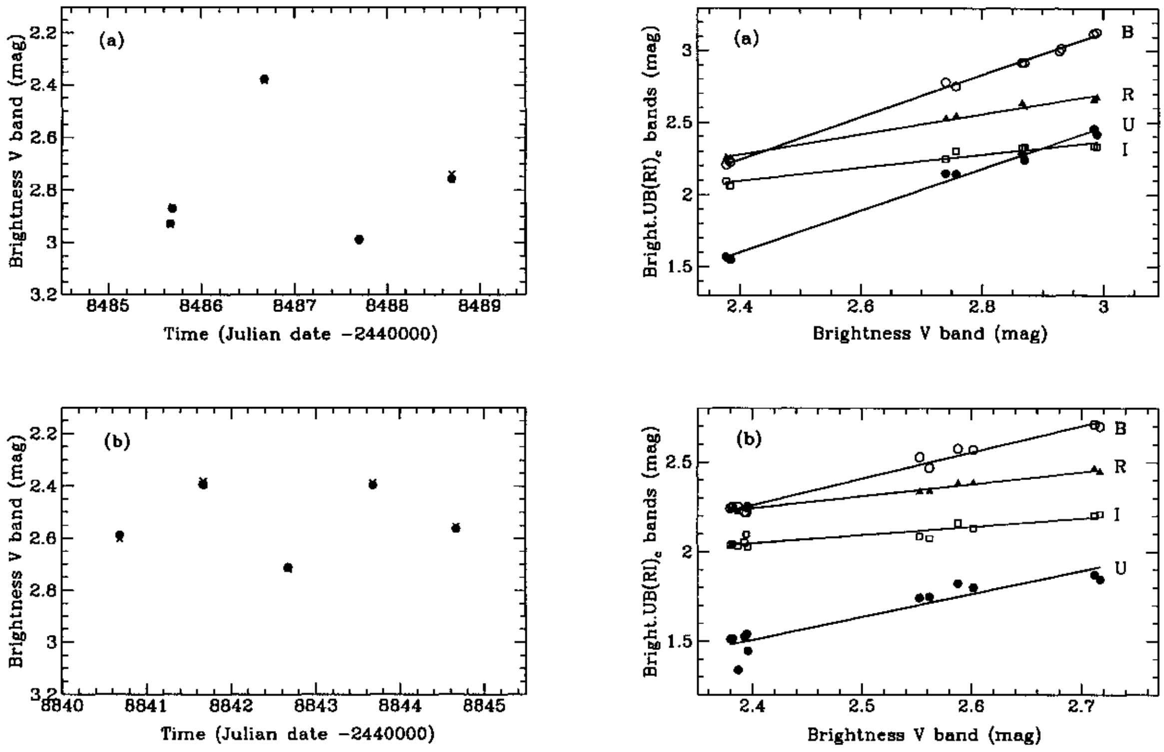

Fig. 12. Photometric observations of LkH$_\alpha$264 in (a) August 1991 and (b) August 1992.

brightness. When the maximum does not correspond to a hot spot crossing the central meridian or to an eclipsed cool spot[3], the values obtained for the spot size and temperature difference with the photosphere are lower limits; the same applies for the minimum, when it does not correspond to the eclipsed hot spot or the cool spot crossing the central meridian.

The amplitudes calculated from the difference between maximum and minimum brightness are affected by the errors in both values, especially the minimum (when the integration times should be longer than usual). For this reason, and taking into account the correlation between the variability in all the bands, we have calculated the *estimated amplitudes*, that is, the product of the V band *maximum-minimum amplitude* by the slope of the regression lines fitted to the representation of the UB(RI)$_C$ bands against the V band. These UB(RI)$_C$ *estimated amplitudes* take into account all the information of the light curve and the fact that the V band is one of the bands with smaller errors. We have compared them with the observed *maximum-minimum amplitudes* and when differences were larger than 0.05 mag, low weight was given to the *maximum-minimum amplitudes* in the fit by the star spot model. This technique was used because we were looking for the cause of the variability, which has time scales of days, and not the short term (hours – days) variability; although sometimes it is not so easy to distinguish them. Peaks superimposed onto the analyzed variability will be discussed in the Sect. 3.3.

[3] That could be, for example, because we finished our observations before the hot spot crossed the central meridian.

3.2. *Comparison of the observations with the models*

The results of the comparison between the observations and the spot models for each star are presented in Tables 10 and 11. Table 10 contains the observed amplitudes of the UBV(RI)$_C$ light curves for each object and observing run and the ranges of spot temperature and area that best fit these observations. In Table 11 we present the computed UBV(RI)$_C$ amplitudes corresponding to the spots that define the spot temperature and area ranges indicated in Table 10. In this section we comment on the results for each object; brief remarks are given when the inhomogeneous circumstellar envelope fits the observations. We consider that a spot or an inhomogeneous circumstellar envelope reproduces the amplitudes of the UBV(RI)$_C$ bands light curves when the difference between the observations and the model results are smaller than 0.03 mag. When a spot fits the observed amplitudes, a range of spot temperatures (T_s) and areas are indicated for each observing run. Changes in the star spots, or the fact that we observe different segments of the light curve, can explain why the T_s and size ranges do not always overlap from one observing run to another. In some cases only the BV(RI)$_C$, or even the V(RI)$_C$ amplitudes, can be compared with the models, because the U or the U and B amplitudes are much larger or smaller than expected from the behavior of the other amplitudes. In that cases the difference between the observed U (or U and B) amplitude and those due to the spots that fit the BV(RI)$_C$ (or V(RI)$_C$) amplitudes are given.

As mentioned previously, the comparison between the *estimated* and the *maximum-minimum amplitudes* is a good indica-

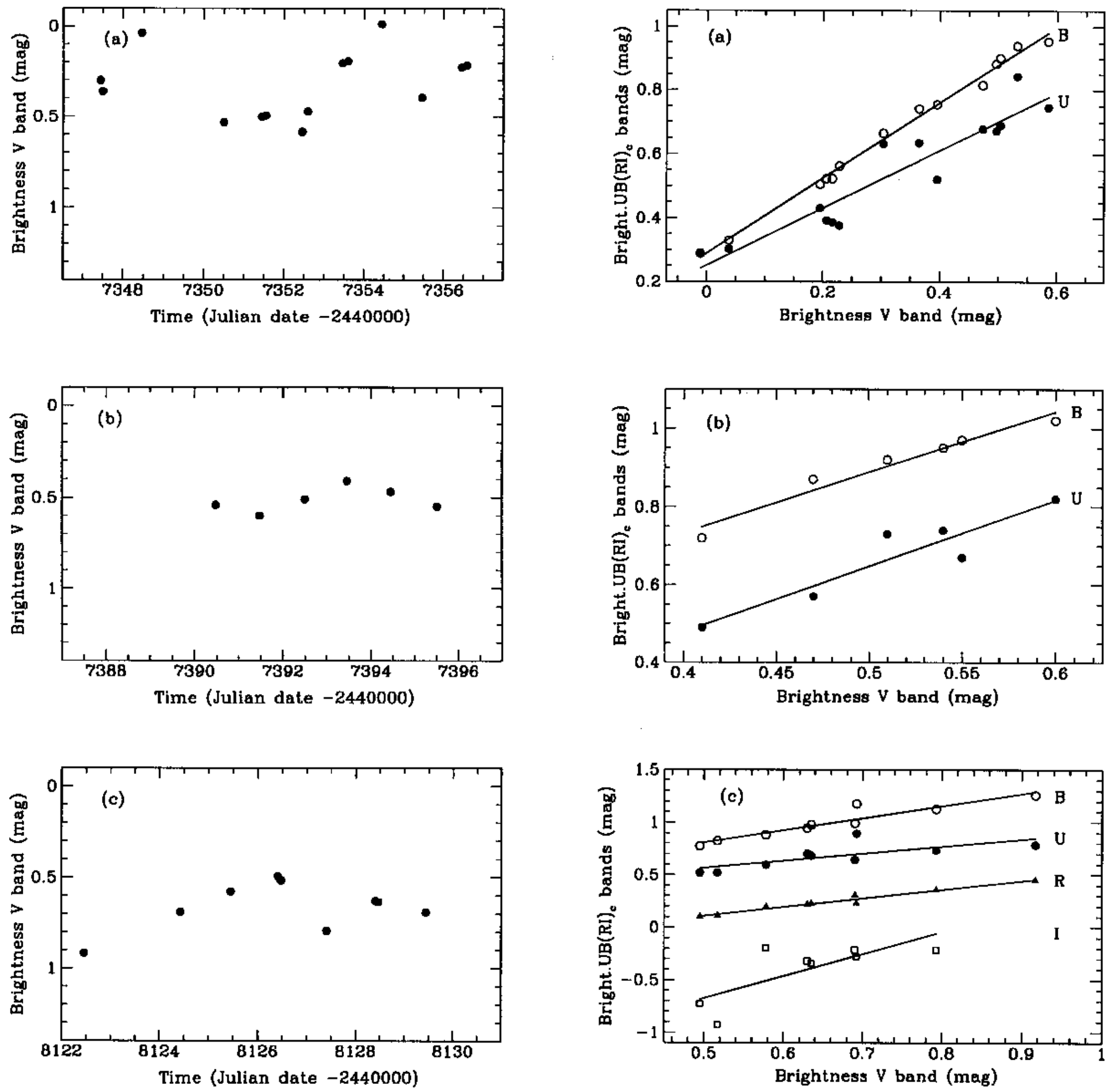

Fig. 13a–f. Photometric observations of AS 353 in **a** July 1988, **b** August 1988, **c** August 1990, **d** June and July 1991, **e** August 1991 and **f** August 1992.

tor of the precision of the observed amplitudes. To quantify the quality of the *estimated amplitudes* we have calculated the correlation coefficient[4] of the regression line of the UB(RI)$_c$ bands against the V band (least squares method). When this coefficient is smaller than 0.90, its value is indicated.

LkH$_\alpha$325. The amplitude of the variability in the V band is 0.15 mag but the observational errors seem to be larger than 0.03 mag. For this reason we have not analyzed the origin of its variability.

DI Cep. The correlation is good among all bands. The observations are reproduced by hot spots, except the amplitude of the U band in August 1991, which is 0.16 mag larger than expected from the hot spot that fits the BV(RI)$_c$ bands.

V1331 Cyg. It has been classified as a *continuum* star in the Herbig and Bell (1988) catalog. Here we adopt the effective temperature indicated by Chavarría-K. (1981).

The correlation coefficient for the U band is always between 0.80 and 0.91 and for August 1991 we have cc_i=0.87. For August 1988 the observed amplitudes are reproduced by an inhomogeneous circumstellar envelope and also by a cool or a hot spot, but this is probably due to the lack of information on the R$_c$ and I$_c$ bands. For June and July 1991 any cool spot with temperature below 5800 K can reproduce the observations and so can an inhomogeneous circumstellar envelope. During the other observing runs the change of the amplitude with wave-

[4] This coefficient will be indicated by cc_x, where the x denotes the photometric band.

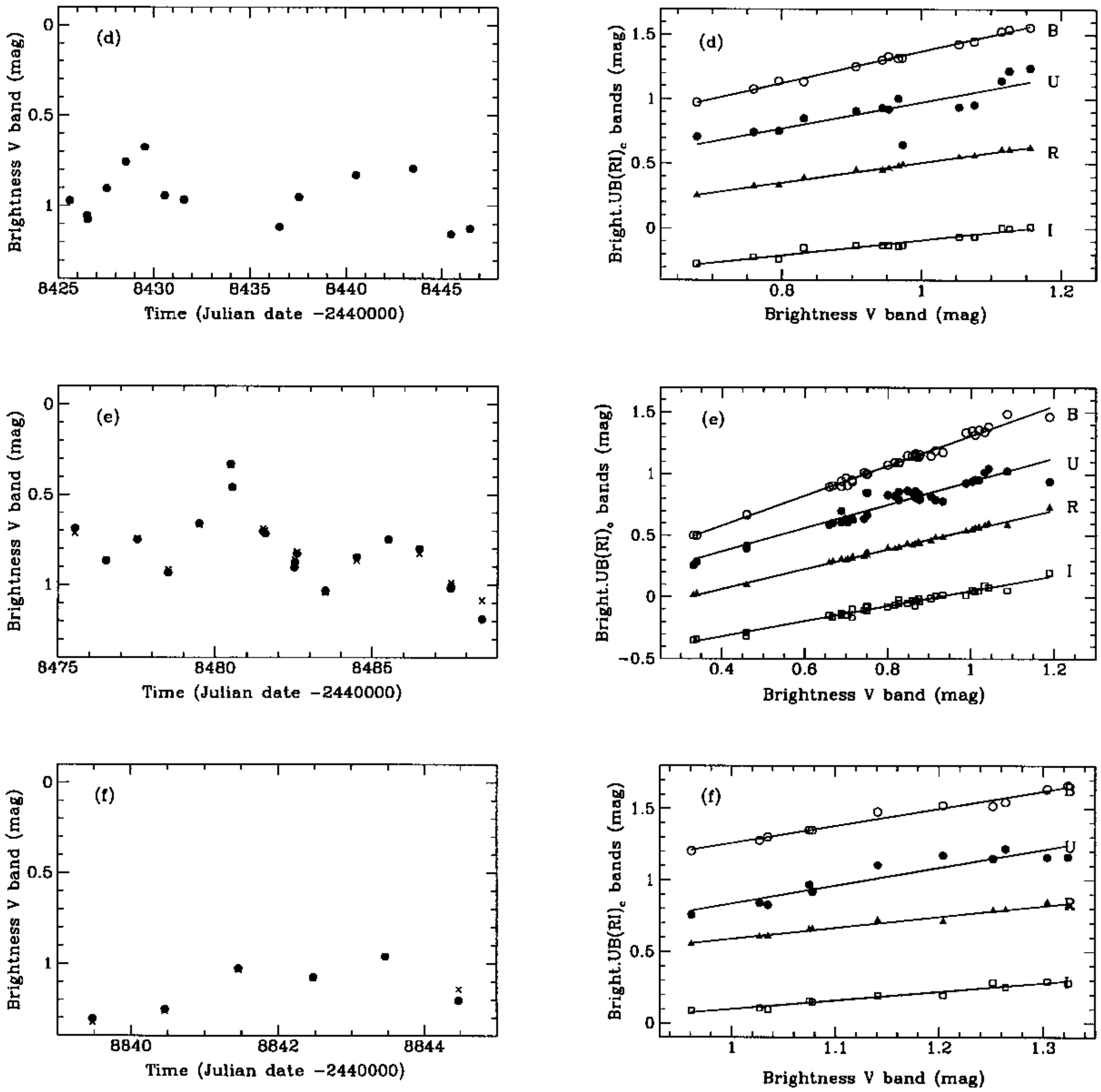

Fig. 13. (continued)

length does not follow the usual pattern (increasing amplitude with decreasing wavelength) and cannot be reproduced by any of the models. This star shows a behaviour closer to the Ae/Be Herbig stars, as was indicated by Shevchenko et al. (1991).

V1121 Oph. The correlation among the different bands is poor. During June and July 1991: cc_u=0.86, and cc_r=0.86; during August 1991 cc_u=0.58 and during August 1992 cc_r=0.73 and cc_i=0.72. The June and July 1991 observations are fitted by a hot spot, as are the August 1992 observations. On the other hand, a cool spot can reproduce the August 1991 observations, although this fit is uncertain because the amplitude in the U band seems to be affected by another phenomenon (the amplitude observed in the U band is close to that of the B band, in contrast to the other observing runs).

LkH$_\alpha$264. The variability observed in all the bands correlates very well. The BV(RI)$_c$ amplitudes are reproduced by hot spots, while the U amplitudes are around 0.6 and 0.2 mag lower than predicted for August 1991 and 1992, respectively. It is not possible to reproduce the observations with a cool spot. An inhomogeneous circumstellar envelope reproduces the August 1992 observed variability.

AS 353. The observations correspond to both A and B components but we have not taken into account the contribution of the B component in the spot models, because we did not know its energetic distribution. AS 353 is a *continuum* star and from the comparison of its spectral distribution with other active CTTSs we have adopted an effective temperature of 4000 K.

The variability in all the bands correlates very well, except for the U and I bands in August 1990, with cc_u=0.74 and

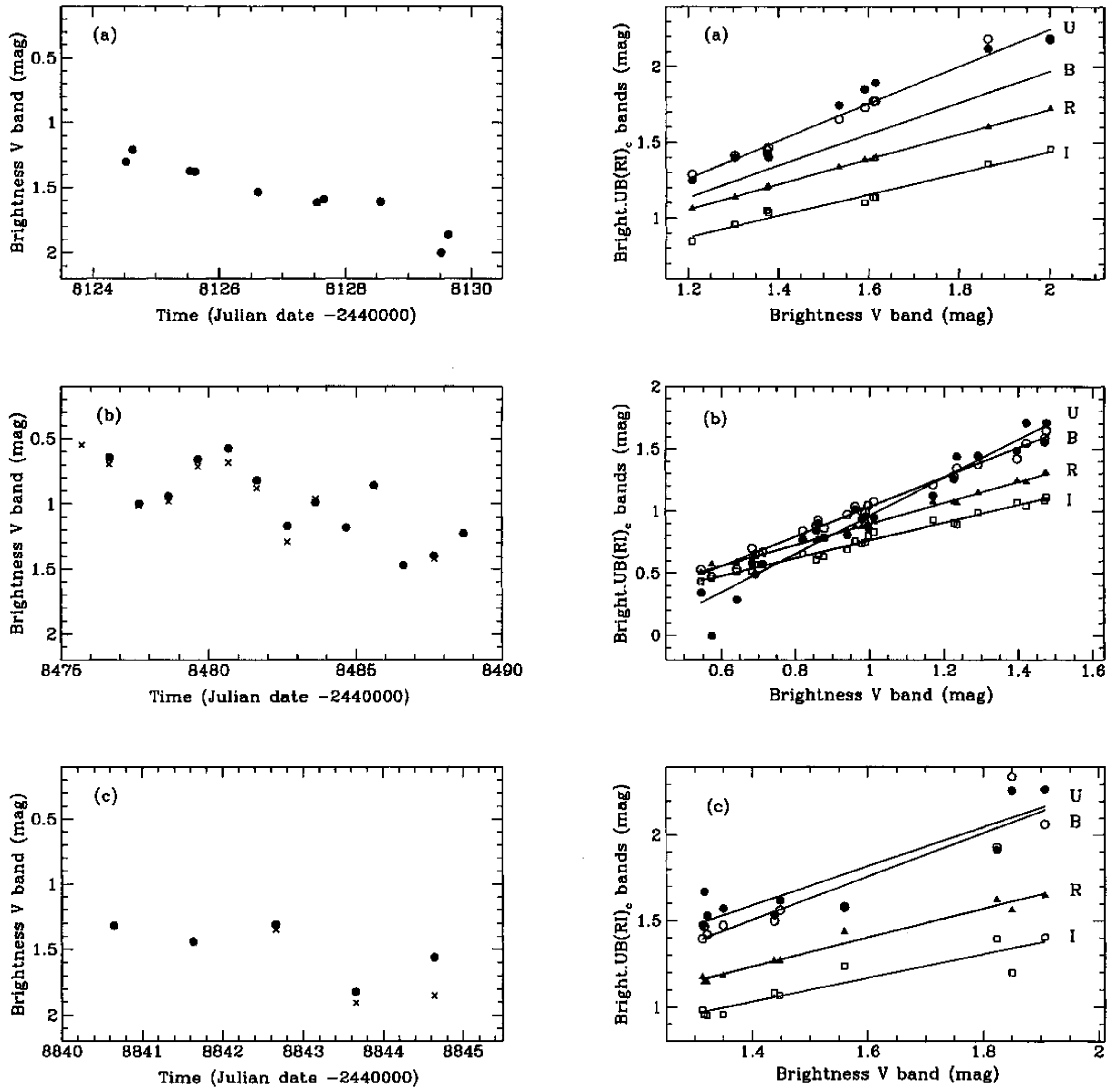

Fig. 14a–c. Photometric observations of BM And in **a** August 1990, **b** August 1991 and **c** August 1992.

cc_i=0.69. The amplitudes in the U band are always smaller or equal to the amplitudes in the B band, so we have constrained the comparison with the models to the BV(RI)$_c$ bands. The result of the comparison for the 1988 observations is not reliable because two amplitudes (those in the B and V bands) give very little constraint on the spot temperature and size. For 1991 only hot spots fit the observations, while both cool and hot spots reproduce the other observing runs. The differences between the observed U amplitudes and those predicted by the fitted hot spot models are -0.4, -0.3, -0.6 and -0.2 mag, respectively, for the last four observing runs. For the cool spots the differences are -0.2, -0.2 and -0.1 mag, respectively. For June and July 1991 and August 1992 the BV(RI)$_c$ amplitudes are also reproduced by an inhomogeneous circumstellar envelope.

The long term (years) variability we have observed presents amplitudes changing with wavelength in such a way that cannot be reproduced by any star spot or by an inhomogeneous circumstellar envelope.

BM And. The correlation between the variability in all the bands is very good. The *estimated* amplitude for the U band in August 1991 is some tenths of magnitude larger than the observed. The best fit corresponds always to a cool spot. In the case when the observations are also reproduced by a hot spot, the spot must be unusually large. For August 1990 an inhomogeneous circumstellar envelope also reproduces the observed amplitudes.

AS 205. The correlation coefficient of the U band during June and July 1991 is cc_u=0.38. During August 1992: cc_u=0.68,cc_b=0.76 and cc_i=0.85. The large errors of the measurements reduce the reliability of the results of the comparison

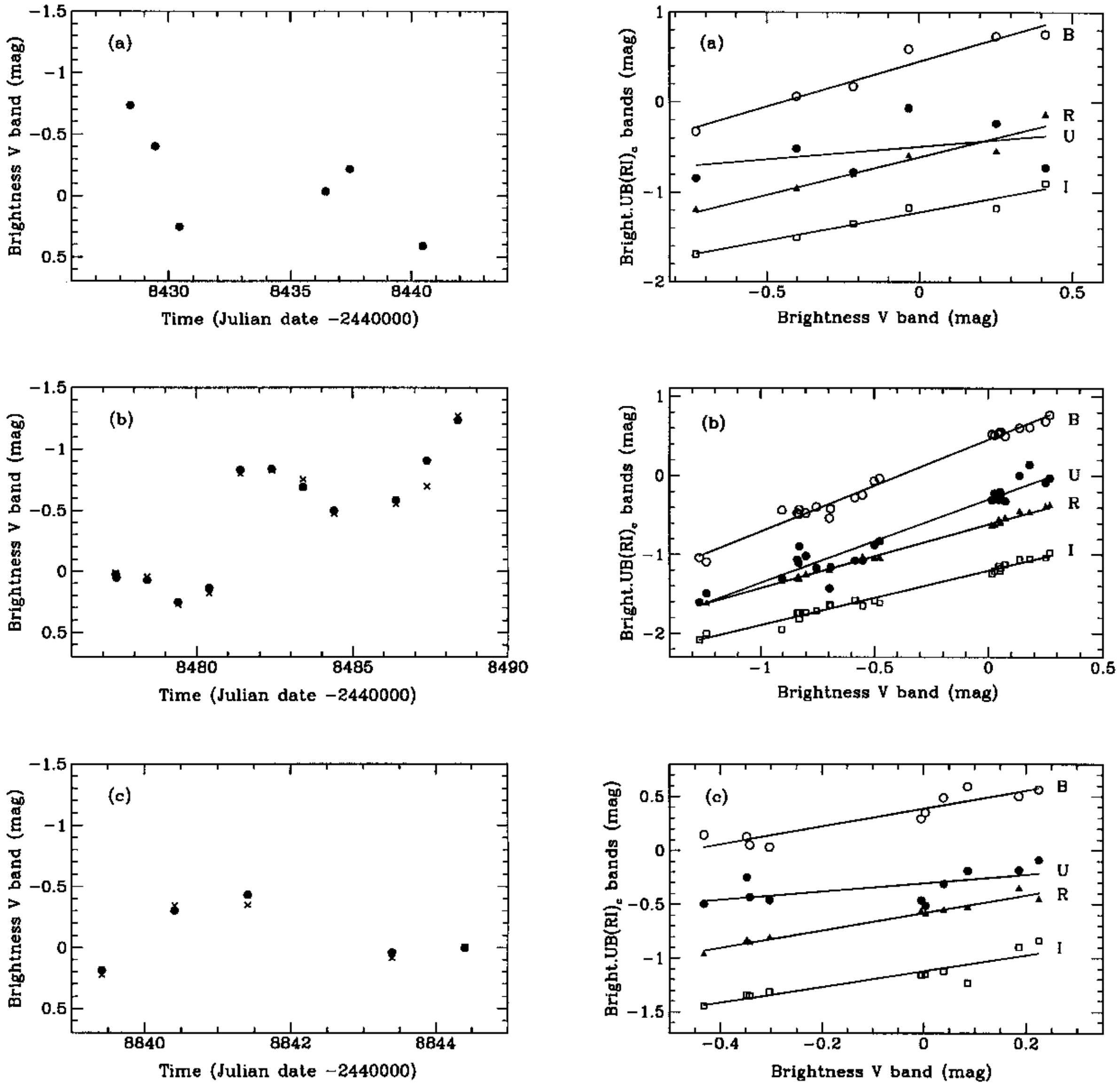

Fig. 15a–c. Photometric observations of AS 205 in **a** June and July 1991, **b** August 1991 and **c** August 1992.

with the models. It is clear that the amplitudes observed in the U band and, sometimes, in the B band are smaller than or equal to the amplitudes observed at longer wavelengths. For this reason we have restricted ourselves to the $V(RI)_c$ bands in the comparison with the stellar spot model. We found that the best fits give U and B amplitudes considerably larger than the observed ones: in June and July 1991 the excess in the B band is around 0.5 mag for the hot spot and 0.4 for the cool one. In August 1991 the excesses are around 1.0 mag in the U band and 0.2 in the B band, and in August 1992, around 0.45 mag in the U band and 0.4 in the B band.

Summarizing, in general, hot spots reproduce the variability observed in 5 stars (DI Cep, V1121 Oph, $LkH_\alpha 264$, AS 353 and AS 205), cool spots reproduce the variability observed in BM And and for V1331 Cyg and $LkH_\alpha 325$ there is no clear mechanism. An inhomogeneous circumstellar envelope reproduces the variability observed in some observing runs for V1331 Cyg, $LkH_\alpha 264$, AS 353 and BM And.

3.3. Variabilities with different time scales

The smooth variability with a time scale of days is reproduced by hot or cool spots for most of the variable stars in our sample. The presence of hot spots was reported in the 80's without ambiguity for six TTSs: DN Tau, GI Tau and GK Tau (Vrba et al. 1986), BP Tau (Vrba et al. 1986; Simon et al. 1990), DF tau (Bouvier & Bertout 1989) and DH Tau (Vrba et al. 1989). Later on, COYOTES I detected hot spots on another 5 TTS (DE Tau, DG Tau, IP Tau, GM Aur and TAP 57NW) and confirmed the result for DF Tau and GK Tau (Bouvier et al. 1993a). Ten stars out of these 11 are CTTS and TAP 57NW, the only one classi-

Table 10. Ranges of spot temperature, T_s, and area of the star spots that reproduce the observed UBV(RI)$_c$ amplitudes (see text). Spot temperatures greater than the effective temperature of the star (T_{eff}) are indicated in italics.

Object	Observational run	Observed amplitudes Δm_U	Δm_B	Δm_V	Δm_R	Δm_I	T_{eff}(K)	Spot model (T_s (K), area) range
DI Cep	August 1991	.53	.26	.15	.13	.12	5440	*(5600, 0.414)(8300, 0.012)* (5100, 0.199)(5300, 0.487)
DI Cep	August 1992	.53	.31	.21	.17	.14	5440	*(7400,0.026) (8300,0.015)*
V1331 Cyg	July 1988	.35	.37	.32			7350	
V1331 Cyg	August 1988	.35	.26	.22			7350	*(7700, 0.411)(10500, 0.030)* (5300, 0.104)(7100, 0.609)
V1331 Cyg	August 1990	.37	.27	.22	.19	.31	7350	
V1331 Cyg	Jun.Jul.1991	.30	.29	.24	.22	.22	7350	Any T_m up to (5800,0.123)
V1331 Cyg	August 1991	.27	.17	.18	.16	.17	7350	
V1331 Cyg	August 1992	.2:	.23	.23	.23	.22	7350	
V1121 Oph	Jun.Jul.1991	.49	.24	.15	.16	.07	4400	*(5800,0.017) (8100,0.002)*
V1121 Oph	August 1991	.46	.41	.34	.29	.24	4400	(3400,0.117) (4100,0.261)
V1121 Oph	August 1992	.72	.33	.21	.16	.14	4400	*(6600,0.011)*
LkH$_\alpha$264	August 1991	.88	.91	.61	.41	.26	4400	*(6000,0.049) (6400,0.035)*
LkH$_\alpha$264	August 1992	.47	.45	.32	.23	.18	4400	*(4600,0.377) (6200,0.019)*
AS 353	July 1988	.46	.66	.60			4000	(2500,0.172) (3500,0.262)
AS 353	August 1988	.33	.30	.19			4000	*(4100, 0.415)(7000, 0, 003)* (3400, 0.094)(3900, 0.434)
AS 353	August 1990	.27	.49	.42	.35		4000	*(4200, 0.371)* (2800, 0.124)(3800, 0.405)
AS 353	Jun.Jul.1991	.53	.59	.48	.37	.28	4000	*(4200, 0.443)(4400, 0.189)* (3600, 0.247)(3850, 0.636)
AS 353	August 1991	.71	.97	.80	.64	.47	4000	*(4250,0.668) (4300,0.525)*
AS 353	August 1992	.40	.43	.34	.29	.20	4000	*(4200, 0.287)(4500, 0.098)* (3600, 0.184)(3900, 0.725)
BM And	August 1990	.64	.49	.41	.34	.29	4400	*(4600, 0.478)* (3900, 0.226)(4200, 0.495)
BM And	August 1991	1.36	1.12	.93	.80	.68	4400	(3700,0.374) (3900,0.475)
BM And	August 1992	.57	.56	.53	.46	.43	4000	(1500,0.140) (3000,0.148)
AS 205	Jun.Jul.1991		1.08	1.15	1.05	.79	4400	*(4900, 0.627)* (3900, 0.605)(4000, 0.756)
AS 205	August 1991	1.49	1.79	1.51	1.23	1.03	4400	*(5000,0.694) (5100,0.550)*
AS 205	August 1992	.42	.41	.74	.68	.63	4400	(2000,0.194) (3200,0.228)

fied as WTTS, is a binary system, so characteristics of the spot could be affected by the companion. In our sample, hot spots reproduce the observations for 5 stars.

Superimposed onto that smooth variability with a time scale of days, some stars show peaks of brightness lasting usually 2 or 3 days, e.g. Figs. 9 and 13. We have calculated the amplitude of these peaks in the five bands and we have tried to reproduce them with the star spot model. We have found that the nature (cool or hot) of the spot reproducing these brightness peaks is the same as that of the spot that reproduces the "whole" light curve; in addition, the anomalous behaviour observed at the shorter wavelengths (U band) for some stars is also present. It seems that we are observing two kinds of variability, with different amplitudes and time scales, but of similar nature and, perhaps, origin. If the rotational periods of CTTSs are around 8 days, as found by Bouvier et al. (1993a) and Edwards et al. (1993), this 2-3 days variability cannot be modulated by rotation; thus, instabilities in the accretion process or a short-lived hot spot must exist.

The long time scale variability noticed in AS 353 has also been observed for DI Cep. This star showed a decrease of brightness from 1978 to 1980 in the U, B and V bands, at a rate of 0.1 mag/year (Herbst et al. 1995). For both stars the long time scale variability is, if not periodic, at least a recurrent phenomenon. AS 353 presented a brightness of 12.7 mag in the V band in 1975 and of 12.46 mag sometime before 1978 (Cohen & Kuhi 1979; Kopatskaya & Shulov 1978), while it decreased in brightness from 11.7 mag in July 1988 to 12.6 mag in August 1992. DI Cep presented in 1991 and 1992 an average value in the V band similar to that of 1978 (11.3 mag). Since the amplitude of this variability does not increase as wavelength decreases, the models discussed cannot account for the variability; nevertheless, the superposition of two phenomena can reproduce

Table 11. For each star and observational run the amplitudes of the UBV(RI)$_c$ light curves corresponding to the spot models indicated in Table 10 are presented. Each model is characterized by the effective temperature of the star (T_{eff}), the spot temperature (T_s), and its area. Spot temperatures greater than the effective temperature of the star are indicated in italics.

Object	Observational run	Spot model						
		T_{eff}(K)	(T_s (K), area)	Δm_U	Δm_B	Δm_V	Δm_R	Δm_I
DI Cep	August 1991	5440	*(5600,0.414)*	.29	.23	.18	.15	.12
DI Cep	August 1991	5440	*(8300,0.012)*	.45	.27	.17	.12	.09
DI Cep	August 1991	5440	(5100,0.199)	.28	.23	.18	.15	.12
DI Cep	August 1991	5440	(5300,0.487)	.28	.23	.18	.15	.12
DI Cep	August 1992	5440	*(7400,0.026)*	.51	.33	.22	.16	.12
DI Cep	August 1992	5440	*(8300,0.015)*	.55	.34	.20	.15	.11
V1331 Cyg	August 1988	7350	*(7700,0.411)*	.33	.27	.21	.18	.15
V1331 Cyg	August 1988	7350	*(10500,0.030)*	.39	.27	.19	.15	.12
V1331 Cyg	August 1988	7350	(5300,0.104)	.32	.29	.25	.23	.20
V1331 Cyg	August 1988	7350	(7100,0.609)	.33	.27	.21	18	.15
V1331 Cyg	Jun.Jul.1991	7350	(300,0.082)	.29	.28	.27	.25	.25
V1331 Cyg	Jun.Jul.1991	7350	(5800,0.123)	.33	.29	.25	.21	.19
V1121 Oph	Jun.Jul.1991	4400	*(5800,0.017)*	.46	.28	.18	.13	.09
V1121 Oph	Jun.Jul.1991	4400	*(8100,0.002)*	.53	.25	.12	.08	.05
V1121 Oph	August 1991	4400	(3400,0.117)	.43	.39	.34	.30	.26
V1121 Oph	August 1991	4400	(4100,0.261)	.48	.39	.31	.26	.21
V1121 Oph	August 1992	4400	*(6600,0.011)*	.68	.38	.22	.15	.10
LkH$_\alpha$264	August 1991	4400	*(6000,0.049)*	1.40	.90	.57	.43	.30
LkH$_\alpha$264	August 1991	4400	*(6400,0.035)*	1.52	.95	.57	.42	.29
LkH$_\alpha$264	August 1992	4400	*(4600,0.377)*	.54	.42	.32	.26	.21
LkH$_\alpha$264	August 1992	4400	*(6200,0.019)*	.78	.47	.28	.20	.14
AS 353	July 1988	4000	(2500,0.172)	.71	.67	.62	.58	.54
AS 353	July 1988	4000	(3500,0.262)	.82	.69	.57	.49	.41
AS 353	August 1988	4000	*(4100,0.415)*	.35	.28	.21	.18	.14
AS 353	August 1988	4000	*(7000,0,003)*	.71	.33	.16	.10	.06
AS 353	August 1988	4000	(3400,0.094)	.30	.27	.22	.20	.16
AS 353	August 1988	4000	(3900,0.434)	.35	.28	.21	.18	.14
AS 353	August 1990	4000	*(4200,0.371)*	.66	.52	.39	.32	.25
AS 353	August 1990	4000	(2800,0.124)	.49	.46	.42	.38	.34
AS 353	August 1990	4000	(3800,0.405)	.62	.50	.39	.33	.26
AS 353	Jun.Jul.1991	4000	*(4200,0.443)*	.76	.59	.45	.37	.29
AS 353	Jun.Jul.1991	4000	*(4400,0.189)*	.84	.63	.46	.37	.28
AS 353	Jun.Jul.1991	4000	(3600,0.247)	.66	.55	.45	.38	.31
AS 353	Jun.Jul.1991	4000	(3850,0.636)	.73	.58	.45	.38	.31
AS 353	August 1991	4000	*(4250,0.668)*	1.25	.99	.77	.65	.52
AS 353	August 1991	4000	*(4300,0.525)*	1.28	1.00	.77	.64	.51
AS 353	August 1992	4000	*(4200,0.287)*	.54	.42	.31	.26	.20
AS 353	August 1992	4000	*(4500,0.098)*	.64	.46	.32	.26	.19
AS 353	August 1992	4000	(3600,0.184)	.49	.41	.33	.28	.23
AS 353	August 1992	4000	(3900,0.725)	.54	.43	.34	.28	.23
BM And	August 1990	4400	*(4600,0.478)*	.65	.51	.39	.33	.26
BM And	August 1990	4400	(3900,0.226)	.62	.52	.42	.36	.30
BM And	August 1990	4400	(4200,0.495)	.63	.51	.40	.33	.27
BM And	August 1991	4400	(3700,0.374)	1.33	1.14	.94	.81	.68
BM And	August 1991	4400	(3900,0.475)	1.38	1.14	.91	.78	.64
BM And	August 1992	4000	(1500,0.140)	.57	.54	.51	.48	.46
BM And	August 1992	4000	(3000,0.148)	.59	.55	.50	.46	.42
AS 205	Jun.Jul.1991	4400	*(4900,0.627)*	1.94	1.53	1.18	.99	.80
AS 205	Jun.Jul.1991	4400	(3900,0.605)	1.81	1.48	1.18	1.00	.82
AS 205	Jun.Jul.1991	4400	(4000,0.756)	1.85	1.50	1.18	1.00	.81
AS 205	August 1991	4400	*(5000,0.694)*	2.42	1.93	1.50	1.26	1.02
AS 205	August 1991	4400	*(5100,0.550)*	2.51	1.97	1.50	1.26	1.00
AS 205	August 1992	4400	(2000,0.194)	.81	.77	.72	.69	.65
AS 205	August 1992	4400	(3200,0.228)	.93	.85	.76	.69	.60

this change of brightness: the disappearing of a inhomogeneous circumstellar envelope and the development of a cool spot.

3.4. Anomalous behaviour in the U band

Three different behaviours are found when comparing the observed amplitudes with the star spot and the inhomogeneous circumstellar envelope models: *i)* the model fits the observations (BM And), *ii)* the model fits the amplitudes observed in the $BV(RI)_c$ bands, but the amplitude observed in the U band is smaller than what is predicted by the model ($LkH_\alpha 264$, AS 353 and AS 205), and *iii)* the model fits the amplitudes observed in the $BV(RI)_c$ bands, but the amplitude observed in the U band is larger than what is predicted by the model (DI Cep and, probably, V1121 Oph).

We discuss the possible explanations for this anomalous behavior. There could be another phenomenon, simultaneous with the hot spot, that affects considerably the emission at short wavelengths (U band). A careful look at the observed amplitudes reported in Table 10 shows that the intensity of the superimposed phenomenon must be variable. For DI Cep (and, probably, for V1121 Oph), the unexpectedly large U amplitudes could be due to hot regions in the surroundings of the stars. A simple model of two hot spots, one at 1000 K above the effective temperature of the star and another at more than 30000 K, generates a sequence of amplitudes in the $UBV(RI)_c$ bands that cannot be fitted by a unique hot spot because the amplitude at the U band is always too large. The observed ultraviolet emission lines and their variability support this hypothesis for DI Dep (Gómez de Castro & Fernández 1996). This very hot region must be related to the hot spot at a few 1000 K above the effective temperature of the star and must corrotate with the star; thus cannot be very far from it.

We have reproduced unexpectedly small U amplitudes adding hot regions that are always visible (like equatorial belts) to the spot model but there are too many free parameters to draw meaninful conclusions. Another possible explanation could be that they are due to a large blue veiling. This veiling, or the hot region being always visible, enhances the continuum at short wavelengths so the amplitude of the variability decreases, because it is measured relative to the continuum. In support of the hypothesis than the lower than predicted U amplitude observed in some stars is due to the dilution effect of blue veiling, one may note that a correlation between $W(H_\alpha)$ and veiling was shown by Hartmann and Kenyon (1990) and Hartigan et al. (1990) and a formula was proposed by Strom et al. (1989). Shortly after this, Basri and Batalha (1990) realized that the veiling correlates better with the H_α flux than with $W(H_\alpha)$ itself. Nevertheless, DI Cep has a large $W(H_\alpha)$ but we do not see such a dilution effect. In this sense we note that Guenther and Hesmann (1993a) concluded that for DR Tau, a very active CTTS, there does not appear to be a simple relation between the line fluxes and the amount of veiling.

These phenomena can explain the anomalous behaviour in the U band both for the variability on a time scale of days and for the superimposed peaks that last 2 or 3 days. Due to the effects of these phenomena on the amplitudes of the light curves, it is probable that hot spots exist on more CTTSs than have been previously reported. From the comparison of the observations and the star spot models for the 10 CTTSs with hot spots found in the literature, one can see that the observed amplitudes are well fitted by a hot spot; only for AA Tau, a CTTS for which Vrba et al. (1989) expected hot spots, lower than expected U and B light curve amplitudes have been reported.

Recently, a study of the UBV variability of TTSs has been presented by Safier (1995). For the analysis of the covariance of the (U-B) and (B-V) colour indexes of a sample of 82 variable pre-main sequence objects, he computes the covariance ellipse of (B-V,U-B) and defines θ as the angle between the major axis of the covariance ellipse and the (B-V) axis (measured counterclockwise). The frequency distribution of θ for his sample (52 objects are CTTSs) is a binomial distribution with maxima around 55° and 155°. It is interesting to note that those stars of our sample with an anomalous behaviour in the U band are located in or near the holes of this distribution. Thus, $\theta_{DICep}=74°$, $\theta_{V1121Oph}=72°$, $\theta_{LkH_\alpha 264}=20°$, $\theta_{AS353}=88°$ and $\theta_{AS205}=116°$.

Variable objects with strange behaviour in the U band, that is, those whose brightness does not increase or decrease in the U band simultaneously with the B and V bands ($\theta > 90°$), have been classified by Safier (1995) as "type P". Safier gives two possible explanations for their variability: *i)* changes in the accretion radius (under a set of very restrictive assumptions) and *ii)* small density fluctuations in the disk, with an optically thin Paschen continuum (provided the accretion radius does not change).

3.5. Irregular variability

In order to investigate how the cool and hot regions that seem to be the cause of the variability of our sample of CTTSs behave in time, we have applied some algorithms to search for periods. From this study we conclude that almost all the stars show an irregular variability and for only one of them, $LkH_\alpha 264$, did we detect a possible periodicity. For this star we have found two possible periods in each observing run[5]: 1.67 and 2.60 days for August 1991 and 1.74 and 2.33 for August 1992. This result does not agree with that of Mendoza et al. (1990), who did not find any periodicity in observations carried out during 11 consecutive nights. This case is similar to that of AS 205: Covino et al. (1992) detected a possible period of 2.7 days in their observations of 1990, nevertheless their observations of 1989 shown an erratic behaviour. This irregular behaviour seems to be common in CTTSs (Gahm et al. 1993).

For most of the variable stars in our sample a smooth variability with a time scale of 5 to 12 days is observed. For some observing runs, sharp variations lasting less than 2 or 3 days are seen. These peaks of brightness must be responsible for at least part of the irregularity of the variations.

[5] It is probably an alias effect because both periods are related by $(P_1^{-1}+P_2^{-1})^{-1} \cong 1$ day, the separation between consecutive measurements.

There is also an irregular variability with time scales of weeks or months in CTTSs as indicated by the existence of quiescent periods, like that observed in BP Tau (Simon et al. 1990). In our sample we have observed quiescent periods for LkH$_\alpha$321 and LkH$_\alpha$324 (see Sect. 2.1).

3.6. Physical environment

Mass loss and accretion processes are physical phenomena linked to the T Tauri phase in the evolution of low mass stars. Their relevance seems to be related to the evolutionary stage of the star - disk system in the sense that more evolved systems (generally thought to be the WTTSs) show a decline in their significance. At the same time, the photometric behaviour of CTTSs and WTTSs shows noticeable differences, as indicated in the introduction. Thus, it is important to investigate how the variability in T Tauri systems is related to indicators tracing mass loss and accretion.

The *constant* stars of our sample show no large ultraviolet or infrared excesses (when measured) and they do not present evidence of high mass loss rates, they have only H$_\alpha$ as an important optical emission line[6]. There are two objects that apparently do not follow this behaviour: LkH$_\alpha$349, which shows a high mass loss rate, and LkH$_\alpha$321, with an H$_\alpha$emission line that sometimes presents a P Cygni profile. Nevertheless, LkH$_\alpha$321 occasionally has brightness variations and for LkH$_\alpha$349 there is no obvious contribution from a circumstellar disk (Hessman et al. 1995). On the other hand, most of the variable objects, except LkH$_\alpha$ 325 and BM And, have spectra with several bright emission lines and some have a high mass loss rate (V1331 Cyg, LkH$_\alpha$264, AS 353 and AS 205). Nevertheless, the variability of LkH$_\alpha$325 in uncertain. We conclude that generally the most active stars have the largest amplitudes for the variability, while the *constant* objects are those with a lower degree of activity. This fact was suggested by Calvet et al. (1983) on the basis of a sample of 12 objects.

In order to analyze the above mentioned trend we have plotted in Fig. 16 the amplitude observed in the V band against the H$_\alpha$ equivalent width (W(H$_\alpha$)). The V band brightness and the H$_\alpha$ emission come from different regions: the first one corresponds to the star surface and, for some stars, to the hot spots, and the H$_\alpha$ line is emitted by the material in the surroundings of the star: the high density regions in the stellar wind or the accretion columns, to which most of the H$_\alpha$ emission can be attributed. For each object we have shown the largest V amplitude and the largest known value for W(H$_\alpha$); the latter was chosen because, if the line flux does not change, it is the closest value to W(H$_\alpha$) at minimum continuum (the stellar continuum, if variability is due to hot regions that add flux to the stellar one).

We can appreciate in Fig. 16 the mentioned trend, i.e. that the objects with largest W(H$_\alpha$) present the largest V amplitudes, while those with W(H$_\alpha$)<30 Å hardly show any variability. There is one object that does not follow the general behaviour: BM And (W(H$_\alpha$) = 43 Å and V amplitude = 0.93 mag).

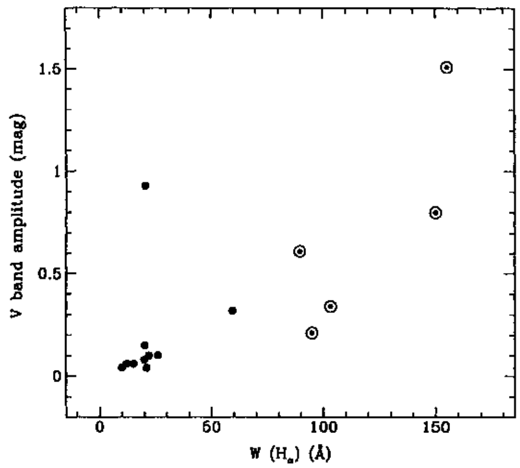

Fig. 16. Maximum observed amplitude in the V band versus the H$_\alpha$ equivalent width of the stars of our sample. Those stars with variability reproduced by hot spots are indicated by the symbol ⊙.

It is a variable star with a W(H$_\alpha$) between 19 and 43 Å (Cohen and Schwartz 1976). It is the only CTTS from our sample for which hot spots do not seem to be the origin of its variability. As mentioned in Sect. 2, Walker (1980) attributed its variability to variable extinction along the line of sight; this explanation is supported by Kardopolov and Rspaev (1980). Nevertheless, Guenther and Hesmann (1993b) explained the observed Balmer and He I line profiles as direct signs of time dependent accretion onto the central star.

The trend observed in Fig. 16 implies a relation between the optical continuum variability and the material in the surroundings of the star. Cabrit et al. (1990) found a correlation among the H$_\alpha$ emission, the luminosity of the forbidden lines and the excess of infrared luminosity. They assumed that the forbidden lines and the H$_\alpha$ emission originate in the stellar winds, while the excess of infrared luminosity is due to the accretion disk. From the aforementioned correlation they concluded that there is a proportionality between the mass loss rate and the mass accretion rate. On the other hand, Calvet and Hartmann (1992) considered the possibility that the H$_\alpha$ emission arises in infalling envelopes rather than winds. In both cases the H$_\alpha$ emission is related to the accretion process. In this picture, the trend we have found might be interpreted as a relation between the observed variability and the accretion process, suggesting that the hot spots responsible for the variability originate in the accretion process and they are probably the regions where matter falls (Bertout et al. 1988)[7].

Vrba et al. (1989, 1993) have studied the relation between the variability of the brightness in the V band and the variability of the W(H$_\alpha$). In their sample they include stars with cool and

[6] We shall consider the strength of the ultraviolet and infrared excess and of the mass loss indicators as a measure of the activity.

[7] Since the measurements compared in Fig. 16 are not simultaneous we are supposing certain recurrence of the optical continuum and H$_\alpha$ behaviour. This recurrence is supported by the long time scale variability commented in Sect. 3.3 and by ultraviolet observations (Gómez de Castro and Fernández 1996).

hot spots and they found that the amplitude observed in the V band increases as the amplitude of the W(H_α) variability increases. They consider this trend to be consistent with the idea that CTTS hot spots are shocked regions formed from magnetically funneled accretion.

Concerning the objects whose brightness remained constant during our observations, we must point out that for most of them the features that characterize the CTTS are quite attenuated; their spectrum is quite similar to the spectra of WTTS, except for their W(H_α), between 10 and 30 Å. These stars, together with the CTTS with cool spots, must be star - disk systems with a lower degree of interaction than the CTTS with hot spots. The constancy of brightness of some of them, in contrast to the variability of the WTTSs, could be due to low magnetic activity, perhaps related to the fact that the rotational velocity is still too low.

Two of the *constant* objects of our sample, LkH$_\alpha$321 and LkH$_\alpha$324, showed almost no variability during our observing runs but they have shown it at other epochs. These quiescent periods could point to an intermediate stage between the high and low activity CTTSs.

4. Conclusions

We have carried out a four year monitoring program on a sample of CTTS, some of which present evidence of high mass loss rates. From our observations and the analysis of the possible origin of the variability, we conclude that:

1. The variable CTTSs of our sample present irregular changes of brightness with time scales of days. Two of the *constant* stars presented quiescent periods lasting weeks or months.
2. For 5 out of the 8 variable stars, the variability with a time scale of days seems to be produced by hot spots, for one of them by cool spots and for two there is no clear mechanism.
3. For some stars other kinds of variability are superimposed on the variability mentioned in the last paragraph: sharp peaks lasting 2 or 3 days (possibly due to instabilities in the accretion process or to short-lived hot spots) and a variability with a time scale of years.
4. Some objects present an anomalous behaviour at shorter wavelengths (U band) that could be explained by other phenomena occurring simultaneously with the star spots. For example, very hot regions related to the hot spots, a large blue veiling or hot regions that are always visible.
5. Considering that the activity is indicated by the strength of those features that characterize the CTTSs, we found that stars with evidence of a high degree of activity show the largest amplitudes for the optical continuum variability, while the *constant* objects are usually those with lower activity.
6. This relation was confirmed when comparing the amplitude of the variability due to hot spots and the H_α equivalent width: the larger the amplitude, the larger the H_α equivalent width. If the H_α emission is related to the accretion process, as suggested by Cabrit et al. (1990) or Calvet and Hartmann (1992), the mentioned trend suggests that the strength of the variability due to hot spots is related to accretion process on the star. Our results are thus an observational support for the theory that explains the hot spots as the regions where the matter from the disk falls (Bertout et al. 1988).

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