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Activity on the classical T Tauri star BP Tauri*

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Abstract. We have made a detailed investigation of the short-term variability in optical light (UBVRI) of the classical T Tauri star BP Tauri. Photometric data (in UBVRI) were collected from Wendelstein Observatory, Germany in 1991, 1992 and 1993 with time-resolutions down to 1 sec and, from binning, fluctuations with total amplitudes down to a few milli-magnitudes could be resolved. Additional observations (in UBV) were collected in China. The total time of monitoring amounts to 135 hours.

The normal state of BP Tau is that it stays completely constant in brightness in all bands, or shows only very slow and smooth changes during a night, to the limit of detection. Brightenings, *events*, occurred on time-scales from 0.6 hours to a few hours but none of these reached a total amplitude > 0.3 mag. in U. As a rule these events do not have the characteristic flare profile as in the lightcurves of stellar surface flares. The total optical energies of the events are a few times 10^{35} erg, with a relatively small spread. The energy distributions at peak flux can be represented by black-body radiation. However, the inferred temperature is very low, 7000 – 8000 K, and not significantly different from that derived for the background veiling. Hence, the events on BP Tau are very different from normal stellar flares.

From power analysis of the time series, we conclude that there is no power indicating frequent and short lasting phenomena, like surface flares. In particular there is no signal in the U band. Such flares would have been expected to be numerous in this high-sensitivity survey, however, if BP Tau had a magnetic surface activity comparable to that of ordinary flare stars. Also, there is no tail in the distribution of events towards smaller amplitudes and shorter durations.

We show that the events of BP Tau are consistent with inhomogeneous mass infall from magnetically controlled accretion between a circumstellar disk and a hot spot at the star. To account for the constancy in temperature and the distribution of events over frequency and amplitude, a model is proposed where the steady accretion of BP Tau is composed of small fragments which arrive close to the star in a random fashion. By simulations we show that such a flow can explain the smooth variations in the veiling and also the sudden occurence of events. In this "fractal" model, each event is composed of several superimposed fragments, which produce the sometimes complex light profiles.

Finally, we find regular long-term variations with a period of 6.6 days, which is in line with (but not exactly) the periods found by others.

Key words: stars: activity; flare: pre-main-sequence – stars: individual: BP Tauri

1. Introduction

Recently, Gahm (1995) reviewed short-term variability, on time-scales of minutes to a few hours, of young stars. It is now established that powerful "flaring" on T Tauri stars (TTS) is very rare, in contrast to indications of the contrary from many previous studies. Gahm et al. (1995a; Paper I) investigated optical light- and spectral variations of selected young stars in some detail. Rapid *events* with total amplitudes of < 0.3 magnitudes in the ultraviolet were found. On the weak-line T Tauri stars (WTTS) some events were identified with stellar surface flares with total energies comparable to the largest ones seen on flare stars. The frequency of such events was found to be consistent with a surface magnetic activity similar to the flare stars of the UV Ceti type, after correction for the larger surface area of the TTS. Not a single event of this type was observed on the two classical T Tauri stars (CTTS) monitored. One of these, VW Cha, was active practically all nights, but all events were smooth, with slow rise- and fall-times, and could be shown to be the result of variable continuous emission superimposed on the stellar photospheric spectrum (the so called veiling). This phenomenon can be related to erratic changes in the mass accretion from a circumstellar disk to the star, since the CTTS (in contrast to the WTTS) are thought to carry circumstellar disks.

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* Based on observations collected at the Wendelstein Observatory and the Yunnan Observatory

The short time-scales favour models where the final accretion occurs under practically free fall, as for instance in the models with magnetically controlled accretion developed by Ushida & Shibata (1984, 1985), Camenzind (1990), Königl (1991) and Gullbring (1994). The excess mass infall needed to account for the total energies of the events is a small fraction of the average accretion rate implied by these models. Hence the general process behind the rapid events appears to be similar to what has been discussed in relation to long-term variability by Basri & Bathala (1990) and Hartigan et al. (1991). Vrba et al. (1989) and Bouvier & Bertout (1989) distinguished between such variations due to irregular mass accretion and periodic variations related to infall towards hot spots or non-axisymmetric rings at the stellar surface (see also Bertout et al. 1988; Simon et al. 1990 and Kenyon et al. 1994). Recently, Herbst et al. (1994) formalized this distinction by defining variability of type II and IIp.

It appears that many CTTS surfaces have cool spots and therefore magnetic activity, like ordinary flares, is expected. However, no evidence for such activity was found in Paper I. In the present article we make a detailed case study of the activity of one classical T Tauri star, namely BP Tauri, a well-known CTTS which has been subject to many investigations and has been reported to show pronounced activity. The aim has been to collect extended series of broad-band flux data at high resolution, both in time and sensitivity. One problem of flare patrol in general is that with a limited part of dark-time available at one location it is difficult to cover the complete evolution of many events. With the ambition to collect extended series of data during each 24 hour period of observations, a net-work of telescopes in China and Europe was organized for two weak-long campaigns - project "Long Baseline". Unusually bad weather prevailed in China, where only a limited amount of data could be collected. This was partly compensated for by the unusually good weather for the season in Europe and a high-quality data bank could be realised with observations carried out also during additional periods. During one run the ground-based observations were combined with X-ray observations using ROSAT. These results will be discussed elsewhere, like more limited data collected for two WTTS. Part of the observations reported here were discussed by Gullbring (1994) in connection to ideas of variable, magnetically controlled accretion.

2. Observed properties of BP Tau

BP Tau, which appears to be single (Ghez et al. 1993), is located in L1495 (Lynds 1962) in the Taurus-Auriga complex of dark clouds at a distance of 140 pc (Elias 1978). Early photometric observations have been summarized by Rydgren et al. (1984). Additional individual measurements have been published by Vrba et al. (1986), Bouvier et al. (1988) and Simon et al. (1990). These works show that BP Tau has a pronounced infrared excess emission and is strongly variable, the total range in B reaching 3 magnitudes (Herbig & Bell 1988). Rapid fluctuations, on time-scales down to min, were displayed by Schneeberger et al. (1979a) and such variations were further discussed by Worden et al. (1981) within the frame-work of frequent surface flaring on TTS, ideas that are also explicit in the classification of BP Tau by Kardopolov et al. (1988).

Table 1. Properties of BP Tauri.

Distance	140 pc
Spectral Type	K5–K7
Period	7.6 days (6.1d; 8.3d)
Rad. vel. (l.s.r.)	15.8 km/sec
$v \sin i$	15.4 km/sec
A_V	0.2–1.4 mag.
L_{bol}	1.4–1.9 $L_\odot$
L_{star}	0.9–1.7 $L_\odot$
T_{eff}	3600 K
M	0.7–0.8 $M_\odot$

Since CTTS often show irregular variations, it is difficult to extract possibly persistent periods which can be tied to stellar rotation. No period was present in the data discussed by Bouvier et al. (1988), but Vrba et al. (1986) found a period of 7.6 days. On a later occasion the period switched from 7.6 to 6.1 days and the star was constant in between (Simon et al. 1990). Shevchenko et al. (1991) reported a 7.6 day period, while Richter et al. (1992) found 8.3 days. This information together with compiled photometric data led Herbst et al. (1994) to classify BP Tau as a Type IIp: periodic variations due to the presence of hot regions at the stellar surface, possibly as the result of accretion. BP Tau becomes redder with decreasing brightness, with a $dB/dV = 1.7$. Additional aspects on the long-term changes have been given by Edwards et al. (1993) and Safier (1995).

BP Tau is a K5 - K7 dwarf with pronounced absorption of Li, a constant radial velocity close to that of the molecular surrounding and a moderate projected equatorial velocity (Joy 1945; Herbig 1977; Vogel & Kuhi 1981; Hartmann et al. 1986; Basri et al. 1991; Duncan 1991; Gameiro & Lago 1993). Superimposed on the K-type spectrum is an excess continous emission, the veiling, which is variable in intensity, but normally stays below 100% of the visible stellar continuum but the Balmer continuous emission is pronounced (Bertout et al. 1988; Hartigan et al. 1989; Basri & Bathala 1990; Valenti et al. 1993). BP Tau is an X-ray source (Walter & Kuhi 1981) and an IRAS source (see e.g. Weaver & Jones 1992), but has not been definitely detected at mm wavelengths (Beckwith et al. 1990). The degree of linear polarization of BP Tau is low (Bastien 1982; Joshi et al. 1987).

In Table 1 we have selected basic parameters for BP Tau. The strong and variable veiling makes it difficult to determine extinction and luminosity, and thereby mass. These estimates have differed since the first attempt by Cohen & Kuhi (1979) before IRAS. We have selected the most recent estimates and given ranges resulting from the works by Beckwith et al. (1990), Bertout et al. (1988), Cohen et al. (1989), Hartigan et al. (1991) and Strom et al. (1989).

Low-resolution FUV spectroscopy was made by Simon et al. (1990) who found the UV continuum and emission line fluxes

Table 2. Observations and variations.

Date (yy.mm.dd)	Length of obs. (hours)	Photometric changes	Notes
91.01.14	4.1	Time resolved event, slow fall	
91.01.16	4.8+5.0	Rise at end of night	China+Wendel.
91.01.18	3.1+7.6	Slow fall and rise	China+Wendel.
92.01.02	3.5	Slow rise	
92.01.03	5.6	Slow rise	
92.01.04	3.0	Slow fall	Cirrus
92.01.06	2.2	Constant	
92.01.07	4.2	Constant	
92.01.10	4.8	Slow rise and fall	China
92.01.11	9.3	Time resolved events	
92.01.12	2.0	Constant	
93.01.14	1.5	Slow fall	
93.01.16	9.0	Slow fall and rise	
93.01.17	9.0	Time resolved events	
93.01.19	2.5	Slow fall at beginning of night	Cirrus
93.01.31	7.5	$\sim$Constant	Moon
93.02.01	6.2	$\sim$Constant	Moon
93.02.02	7.7	$\sim$Constant	Moon
93.02.03	3.2	$\sim$Constant	Moon
93.02.07	4.0	Constant	Moon
93.02.08	6.0	Slow rise at beginning of night	Partly moon
93.02.09	3.6	Constant	Partly moon
93.02.11	3.6	Slow fall at beginning of night	Partly moon
93.02.18	4.9	Slow fall	
93.02.26	1.5	Slow rise	
93.02.27	2.4	Constant	Partly moon
93.03.08	4.5	Constant	Moon
93.03.14	3.6	Slow fall	
93.03.15	1.0	$\sim$Constant	Cirrus

to follow the optical long-term variations. UV studies were also made by Calvet et al. (1985) who studied the relation between Mg II and Ca II flux.

Spectroscopy at high spectral resolution shows that the lower emission lines of H are rather symmetric (Ulrich & Knapp 1979) and Hα has a red asymmetry, a plateau (Mundt & Giampapa 1982), which Calvet & Hartmann (1992) saw as a signpost of magnetically controlled accretion. Evidence for accretion also comes from the wide absorption features, red-displaced to the narrow emission lines of Na D (Schneeberger et al. 1979b). Sometimes time variability of the Balmer line profiles occurs during one night (Knapp 1984; Gahm et al. 1995b) and Sun et al. (1985) found a positive correlation between fluxes of He I λ4471 Å and H I emission.

3. Observations

Broad-band photometric observations of BP Tau were organized at the Mount Wendelstein Observatory, University of Munich, Germany and Yunnan Observatory, China for two periods in January 1991 and 1992. In 1992 Shanghai Observatory, China also participated. Additional observations were collected on Mount Wendelstein in the winter and spring of 1993.

The 0.8 m telescope at Mount Wendelstein was used equipped with a fifteen channel high-speed photometer (MCCP) developed at the University of Munich (Barwig et al. 1987). This instrument measures the object, comparison star and the sky simultaneously by means of fiber fed optics in the five photometric bands U, B, V, R and I. The instrument permits measurements of very high accuracy since both the first order extinction in the atmosphere, and variability in the transparency of the atmosphere can be corrected for. The presence of moonlight or cirrus does not considerably affect the accuracy of the observations. Also, since there are no needs to interrupt the monitoring by observations of sky and comparison star fluxes, very evenly sampled data is achieved. The measurements were made continuously with an integration time of 1 to 2 sec, only interrupted by typically a few min for instrumental calibrations. The comparison star was chosen as to have a brightness and colour similar to the object. The brightness of the comparison star was determined by observations of standard stars. The photometric accuracies obtained for BP Tau are $\pm$0.02 in B, V and R and $\pm$0.09 in U and

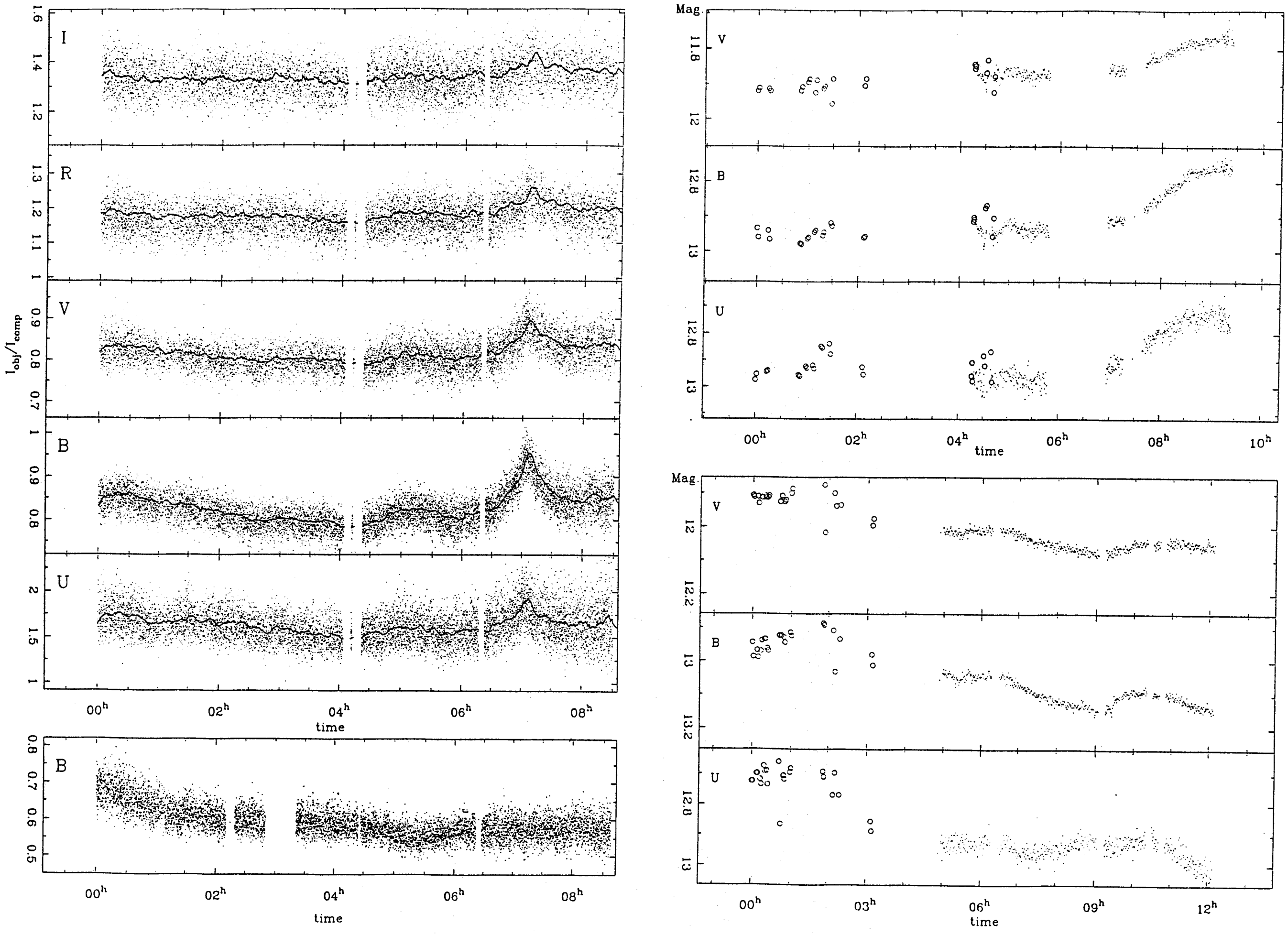

Fig. 1. **a** Wendelstein observations of BP Tau showing one night (JD 2449005) with a distinct flare-like event at the end of the night and another night (JD 2449004, lowest panel - only B shown) with typical slow changes. The points show the typical situation with reduced but unbinned data, while the curve results from the Savitsky-Golay filtering. Note that the range in relative intensity is different for the different filters. **b** Two nights (JD 2448273 and JD 2448275) of UBV data obtained in China (open circles) and Wendelstein (dots, with binning by a running mean of 50 data points). In both diagrams time has been set to zero at the start of the observations.

I when expressed in magnitudes for individual measurements (1 to 2 sec). When data are binned the accuracy improves, and with 40 sec binning we get ± 0.005 in B, V and R and ± 0.009 in U and I. These figures are only slightly worse for nights with moonlight or slight cirrus. Useful data were obtained for BP Tau during a total of 28 nights with this instrumentation.

To distinguish if a brightness variation recorded in the differential photometry in fact was related to BP Tau and not to the comparison star, we always analysed the individual light curves of the stars for which we had only corrected for the sky contribution. Measurements of the count rate of the comparison star during all nights in 1991 to 1993 with good photometric conditions showed no sign of variability of this star. Nevertheless, in the following analyses we will only consider variations, seen in the fully reduced differential photometry, where we have clearly identified that they are related to the target and not to the comparison star.

The observations at the Yunnan Observatory were made with the 1m reflector equipped with a standard UBV photometer. Data could be collected only during 3 out of a total of 14 nights. The photometric accuracies range from about ± 0.04 (rms) in U to ± 0.02 in V. The 1.56m reflector of the Shanghai Observatory was equipped with a UBVRI photometer, but all 6 nights were clouded out.

Table 2 gives an overview of all observations selected for the present analysis, where also the general state of the star is indicated for each night. The Wendelstein data were smoothed in two different ways, by a running mean and by convolving with a Savitsky-Golay filter (see Press et al. 1992). The convolution is very effective since it preserves the amplitudes and durations of the events, both which are normally affected when using a running mean. The left panel of Fig. 1 shows examples of Wendelstein data, where both the individual points (time-resolution of 1 sec) and the convolved lightcurves (with a band-pass of 300 sec) are plotted. The first example is a night with one pro-

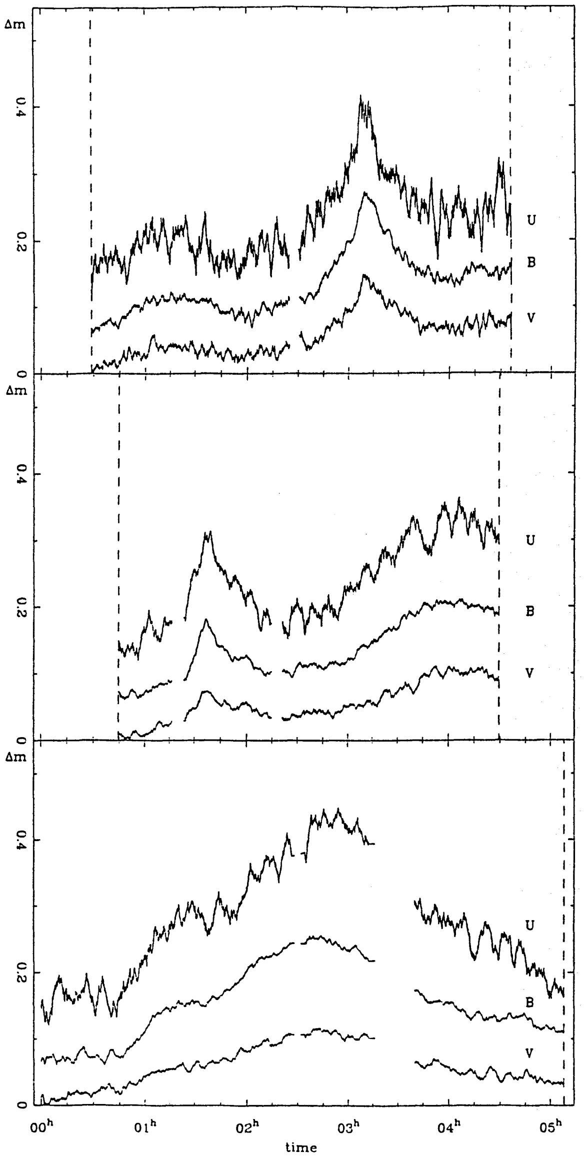

Fig. 2. Further examples of rapid events observed in U, B and V on BP Tau. V is set to zero at the start and with displacements of B and U for clarity. Data were collected outside the vertical dashed frames. The upper panel shows the event displayed in Fig. 1a. The two lower panels show two events observed during one night (JD 2448633). The small-scale fluctuations in U is due to photon noise.

nounced event recorded and it is seen that when the star varies, it does so in all filter bands. Below is a more typical night with only slow and minor changes (only B given). Only during the nights Jan. 16 and 18, 1991 data were collected both in China and Europe and these observations are shown in the right panel where the Wendelstein data are binned into steps of 50 sec. No systematic corrections between the two systems appear. Up to ~12 hours of monitoring was accomplished within a 24 hour period. These nights demonstrate that relatively large variations can occur over several hours but they are slow and without distinct flare-like events. These variations are not related to the rotational modulation of spots on the stellar surface, since the period is about 8 days. In Fig. 2 we display three pronounced rapid events in detail.

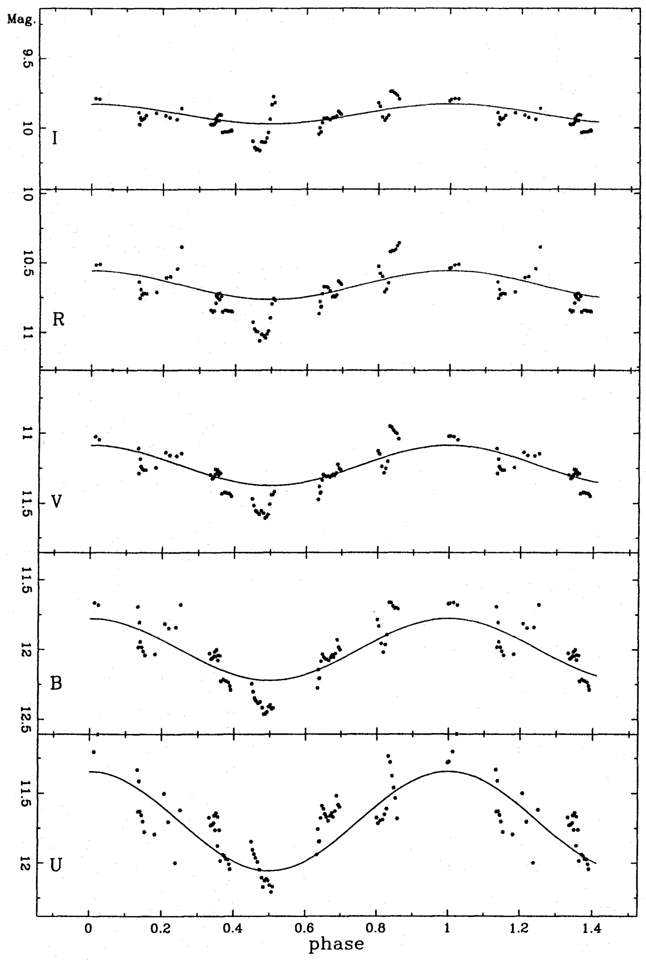

Fig. 3. Phase diagrams over the individual nights in 1993, each night binned by ~3000 points for clarity. Some deviating points, escpecially in the U-band, are from nights with bad atmospheric transparancy but with a reliable mean level. The phase has been calculated with respect to a period of 6.6 days. The solid curves represent a model with a hot spot on the rotating star (see text).

4. Long-term variations

To search for photometric periods we merged observations obtained during 1993 and produced phase diagrams. The nights are unevenly distributed and not suitable even for periodogram analyses. Analysing the merged observations with a Lomb-Scargle algorithm (Lomb 1976; Scargle 1982) gave only a low significance peak at ~6.5 days, mainly due to a heavy aliasing of peaks related to the window function. For further analysis we convolved the data with periods in the interval covering earlier published periods (see Table 1) and produced phase diagrams by tuning the period within the interval. The best fit was found for a period of 6.6 days, with a possible range of about ±0.3 days. The period determination is not accurate but for the published periods of 6.1, 7.6 and 8.3 days there was definitely no good fit to the observations. The time interval covers 13 periods and the fluctuations are very regular as can be seen in Fig. 3. Our data from 1991 and 1992 are not sufficiently extensive to search for periods. Simon et al. (1990) found that BP Tau could change its period within a few weeks, something which has been found also for other CTTS (Fischerström & Gahm 1993). From our data we can not confirm that this occured during the observing period of 1993, but only that the period deviates from that found by other authors. Possibly some process similar to differential rotation operates (Smith 1994) or to a beat phenomenon between the magnetosphere and the disk (Bouvier et al. 1995).

We have applied the following simple spot model to account for the periodic variations:

$$\Delta m(\lambda) = \log[1 - \frac{A_{sp}}{A_{ph}}(1 - \frac{F_{sp}(T_{sp},\lambda)}{F_{ph}(T_{st},\lambda)})] \quad (1)$$

where A_{sp} is the fraction of the projected stellar surface covered by the spot, A_{ph} the visible area of the photosphere, F_{sp} and F_{ph} the spot and photometric fluxes, T_{sp} is the temperature of the spot, T_{st}=4200 K is the stellar surface temperature and $\Delta m(\lambda)$ is the expected amplitude of the photometric variation at wavelength λ. A hot spot with $A_{sp}/A_{ph}=0.04$ and $T_{sp}=7500$ K provided the best fit to the data, where T_{st} was taken as the black-body temperature best corresponding to the star plus remaining veiling at minimum brightness. For a cool spot the solution yields $A_{sp}=0.55$ and $T_{sp}=3500$ K, with T_{st} representing the star plus veiling at maximum brightness. However, this fit could not account for the low amplitudes in R and I.

To summarize, BP Tau showed a distinct periodicity in 1993 of about 6.6 days, variations which to first order can be understood as originating from a hot spot, or non-axisymmetric ring, at the rotating stellar surface. Assuming a radius of ~3 $R_\odot$, as achieved from the position in the Hertzsprung-Russel diagram and with the luminosity and effective temperature of BP Tau taken from Table 1, one obtains an inclination of $i \sim 42°$ when combining with $v \sin i$.

5. Rapid fluctuations

As indicated in Table 2, BP Tau is involved in detectable short-term changes during more than 80% of the nights. However, most of these variations are smooth and slow, on time-scales of several hours, and the total amplitudes of the variations rarely reach above 0.05 magnitudes (~5% in flux) in any band. A few distinct events occurred, when the brightness increased and decreased on time-scales of about 1/2 hour to 2 hours. Two of the time-resolved events were displayed by Gullbring (1994), but will be discussed in more detail below.

The events have the appearance of positive changes in flux and cannot easily be related to for instance rapid openings in a circumstellar dust curtain in front of the star. All events showed evidence of small-scale brightness fluctuations superimposed on the gross variation. For instance, the large event on JD 2448633 in 1992 had oscillations in brightness during its rise, and significant, small-scale structures were present during the decline of the second, rather rapid event on this night. There are differences between these two major events. The first event had a flare-like appearance, with a fast rise-time followed by a slower, exponential decline, while the second, longer lasting event had approximately the same rise- and fall-time. The rapid event observed in 1993 is similar to the rapid event of 1992, with respect to time duration and amplitude, but some differences can be noted. It has an almost perfectly symmetric light profile, with exponential increase and decrease in brightness, but no sign of underlying small-scale variability. However, the amplitudes of these events (in all bands) and the time durations are similar. Also the fast event of 1993 is preceded by slower, but significant fluctuations as in the case of 1992 as if there is a tendency for clustering of events during certain nights. We performed cross-correlation analyses to see if there was any time delay of the events between different colours, but no significant time-lag was found.

5.1. Physical parameters of the events

The energy released by individual events in each photometric band was determined by integration of the light curves over the duration time, and after subtraction of the mean brightness level of the star before the event. A distance to the star of 140 pc and A_V= 0.6 to 0.9 were assumed. The estimates of A_V differ rather much in the literature (see Table 1), but it is of minor importance for the calculation. The so derived broad-band energies, and also the corresponding total luminosities from U to I (E_{opt}) show that the energies involved are comparable to the largest flares seen on flare stars, even though the amplitudes are low. The total energy radiated in U range from 10^{34} to 10^{35} erg and the corresponding range in E_{opt} is 10^{35} to 10^{36} erg, which is comparable to what was found for other CTTS in Paper I. Notice, that events with considerably smaller total energies than the ones recorded would have been detected with this equipment, if they were present.

One can look at an event, either as a distinct phenomenon seen superimposed on the slowly varying background, or as a sudden change in the background (the veiling) itself. For the two cases a χ^2-analysis of the energy distributions of each event was made to estimate their temperature according to the method with the null-hypotheses outlined by Gullbring (1994). One case assumes a variable single black-body continuum and the other case a two component spectrum with a constant K7 V spectrum and a variable black-body.

In the first case a black-body fit to the energy distributions of the star plus the veiling before and during an event is made. An example of the time dependencies of the temperatures derived according to the first case are presented in the upper part of Fig. 4. As for all observations one can see that the derived black-body temperature correlates positively with brightness. The implied change in temperature during a given event is relatively low, however, <500 K. In this picture the veiling increases with a slight shift in dominance towards shorter wavelengths.

For the second case, when subtracting the underlying star, we used different estimates of the spectral energy distribution of the K7 star. The presence of an inverse Balmer jump will have influence on the temperature estimate. The ratio of the flux on the red and blue side of the jump of BP Tauri was given by Valenti et al. (1993) as ~0.85, but is certainly variable in time. For this ratio the contribution in the U band is ~0.06 magnitudes, which leads to a very small overestimate of the temperature. A crucial point is the contribution of the flux from the underlying star. According to veiling measurements by Basri & Batalha (1990) the photospheric contribution is 60 to 70% of the total flux. The uncertainty in this has a small effect on the relative variations of the estimated effective temperatures, but some influence on the determination of the absolute value of the temperature.

Gullbring (1994) found, that under the assumption of the second null-hypothesis, the temperatures were only slightly correlated to brightness. This is true for all nights except for the one on JD 2448275 in 1991 (see Fig. 1b). As an example we show in the lower part of Fig. 4 the result obtained from the active night of 1993. The temperature of the excess flux is very constant, in spite of the light fluctuation.

The event in 1991 is unusual. As seen in Fig. 1b, B and V go towards a minimum in brightness in the middle of the night, while U remains relatively constant. It is difficult to interpret this phenomenon. If an ignition of excess U flux happens to occur when the star fades, then the minimum in U could be filled up. In this case the corresponding event is hotter than the others, but the resulting light profile is not flare-like. Another possibility is that when the star fades to this level, there will be a constant rest of U excess flux composed partly of Balmer emission. This event is the only one with a "hot" signature, but since it is not clearly flare-like, we do not consider it as a sign of surface flare activity.

Under the assumption that the energy release of all the other events can be described by black-body radiation, it is possible to estimate the size of the emitting regions, A_{em}, as

$$A_{em} = \frac{F_{\lambda obs} 4\pi D^2}{\pi B_\lambda(T_{exc})}, \tag{2}$$

where $F_{\lambda obs}$ is the observed specific flux, T_{exc} the temperature of the excess emission and D the distance to the star. The resulting areas are of the order of 10^{21} cm^2, which corresponds to a few per mille of the stellar surface area, similar to the area found for the hot spot.

In both of the cases considered above, the resulting temperatures of the events are low, in particular in comparison to flares seen on the Sun and other stars. This applies also to the rapid event on JD 2448633, which has a flare-like lightcurve. Other events have slow rise-times, comparable to those of the decline, or they are complex. Hence, the star behaves similarly to VW Cha (Paper I) and considering the large total patrol time spent on BP Tau we conclude: *This CTTS is normally very quiescent, with sometimes only small and slow changes in flux during one night, and there is no evidence at all that the rapid events are surface flares of the type seen on flare stars.*

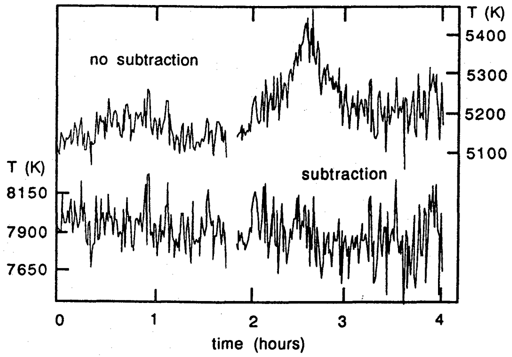

Fig. 4. Example of the derived temperature as a function of time during one rapid event (JD 2449005). The upper part of the figure shows the temperature variation on the assumption of a single black-body. The lower part shows the temperature after subtraction of the underlying stellar flux.

6. Search for "micro-flaring"

Since it has been proposed that the variability of T Tauri stars might be due to the superpositions of a large number of small flares of short duration, we have used our data to search for small-amplitude variability on time-scales less than fifteen minutes. As a criterion of the presence of such events we first required that a fluctuation should be present in at least two bands, especially in U and B. Direct inspection of the lightcurves did not give any evidence of "micro-flares". If present they must "hide" in the noise and we therefore made a study of the frequency distribution of power in the Fourier spectra of the time series. A signal is expected if the flares are numerous enough as to give sufficient power. The analysis must be made with great caution since a number of properties of the data, that are not due to flaring, might induce unwanted power in the Fourier domain: long term trends in the data, gaps in the data sampling and finite time sequences. We have made simulations to see how these effects might influence the power spectra. We found that the presence of small time gaps does not have any severe effect. However, the long-term trends in the data have a substantial influence. Hence, prior to the power analyses all data were detrended with a second degree polynomial, then cancelling slow changes normally occurring during one night.

The calculated power spectra of the detrended data showed only a small amount of power and sometimes no significant power at all. If a significant power was present, the shape of the power spectra could be fitted by a power law. We estimated the slopes of such power laws by fitting a line to the logarithm of the power law. As a lower limit for this fit we omitted power data points (~2 points) for frequencies corresponding to the length of the observation, and as an upper limit we choosed the frequency with no significant power above the frequency independent noise. The power law index cannot be estimated simply by a least square fit to the data. The fit will be aliased by the fact that the power data points are not evenly distributed in the frequency range. The noise in the low-power data points has not a normal distribution, which will weigh the regression

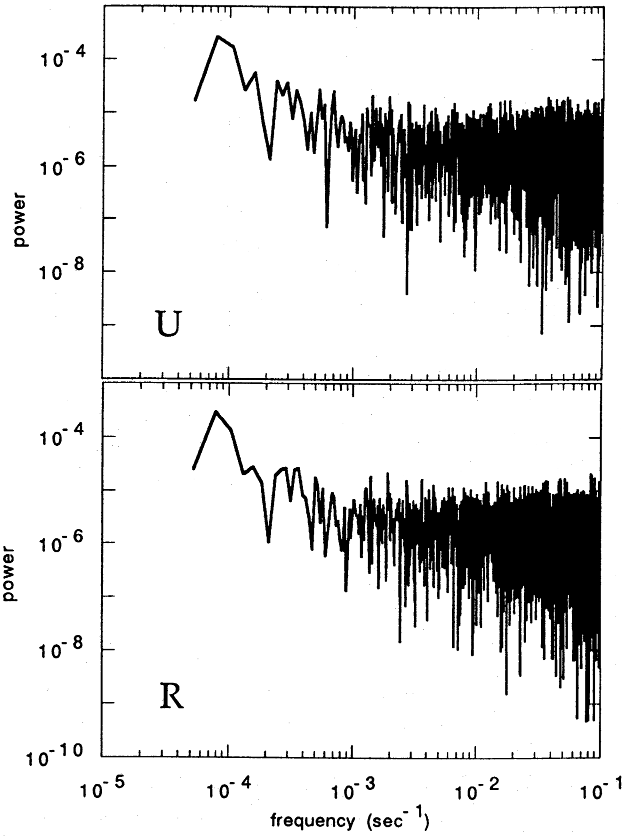

Fig. 5. Representative power spectra (total power=variance) in U and R after a 2 degree polynomial detrending (data from JD2449004). The activity level this night was moderate. The total patrol time was 8.5 hours.

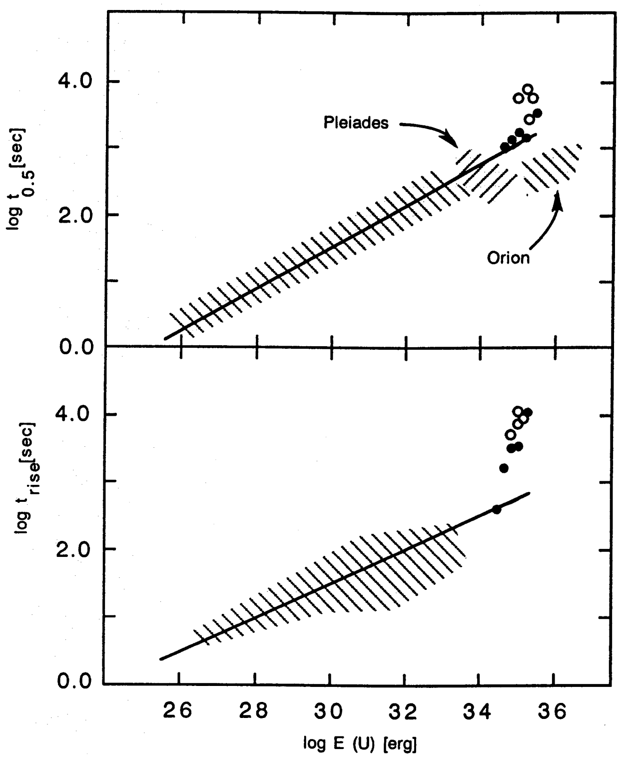

Fig. 6. Rise- and decay-times for flare events as a function of U band energy. The upper panel gives the decay times and the lower panel the rise-times. Shaded areas represent the locations of flares on flare stars and the solid lines represent linear fits to these data (extracted from Petersen 1989). The filled circles mark the positions of the time-resolved events of BP Tau and the open circles the positions of events where only the decay or the rise-time has been observed.

line in an unwanted way at higher frequencies. Therefore, before performing the least-square calculations, we averaged the high-frequency data-points in the power spectra to get an even distribution in frequency. The adopted power indices for different nights and colours were always in the range -1.5 to 0. In Fig. 5, where we show one example of such a power spectrum, one can see that significant power is present only at frequencies corresponding to variations on time-scales longer than ~30 min and are most pronounced at frequencies corresponding to variations of ~1.5 hours or longer. This indicates that the observed power comes from long-term variations during the night, superimposed on the more linear trends already eliminated. The slow residual variations can be identified by direct inspection of the smoothed lightcurves. After detrending the time series with higher order polynomials (of degree ~7) and repeating the power analyses we could not find any significant power above the noise level for any night or colour.

To check the sensitivity of the power analysis, we simulated time series with randomly distributed flare events with an overlying Poisson noise. The flare events were assumed to have a linear rise-time followed by an exponential decline with a duration 10 times longer than the rise-time (to the $1/e$ level). A Gaussian distribution was assumed for the amplitudes and total durations to simulate a range of flare events. We made a number of simulations with different standard-deviations of the Gaussian distributions to check the sensitivity of the method used. We conclude, that *there is no sign of continuous flaring at low levels and time-scales of less than ~1 hour. The achieved power, even after detrending with a second order polynomial, is due to the long-term (>1 hour) nightly variations.*

7. Discussion

7.1. Events as distinct entities

The events occurring on BP Tau have no resemblance to classical surface flares. Gullbring (1994) explained them as a result of inhomogeneous mass accretion. For brightness changes of a few tens of a magnitude, an excess in the accretion rate of the order of 10% is sufficient to account for the energy release. In models where the accretion passes a boundary layer (BL) between the star and the disk the characteristic time-scale for a brightness variability caused by an increase in the accretion rate is longer than the time scales observed here. However, it is not impossible to envision that brightness fluctuations of durations of the order of an hour could origin in a BL and it may be difficult to conclude whether the accretion reaches the stellar surface through a BL or through a magnetosphere. However, other observations of BP Tau like the indication of a hot spot and the shape of the Balmer lines (see for instance Hartmann et al. 1994; Gahm et al. 1995b) strongly support the idea of magnetospheric accretion. Therefore in the following we will use this as our working hypothesis but much of our analysis can also be applied to a BL. In the model of magnetically controlled accretion, which occurs under practically free fall velocity at the end, the short time-scales can be explained: Assume that the excess of the accretion flow is confined in a cylinder rooted at the stellar pole, and that it contains only a slight compression in density above that resulting from the steady accretion along the same cylinder. As a value of the mean accretion rate we adopt 10^{-8} to 2 10^{-8} $M_\odot$ per year (see Gullbring 1994). Then the height (h) of the cylinder is given by $h = v_{ff}m/\dot{M}$, where v_{ff} is the free-fall velocity, m the required mass of the excess material and $\dot{M}$ its accretion rate. For m calculated from the energies given in Section 5.1 (derived from the luminosity and the total time of an event) and with the stellar parameters in Table 1, $h \sim$ 5 10^{10} cm, which is less than 10% of the total length of a bipolar magnetic structure intersecting the accretion disk at 2-3 stellar radii. The time-scale for the deposit of accretion energy from the cylinder is given directly from h as $h/v_{ff} \approx 30$ min. Furthermore, assuming that the observed radiation is thermalized one obtains the time-scale for cooling as $t_{cool} \sim E_{opt}/(\sigma T^4 A_{em})$, where E_{opt} is the total energy integrated from U to I as described above, A_{em} is the emitting area and T the black-body temperature of the thermalized radiation. From the derived temperatures, 7200−8000 K, and areas, $\sim 10^{21}$ cm^2, values of t_{cool} of tens of minutes to hours are obtained.

Both these time-scales, or a combination of, are in agreement with the observations. The longer rise-times of the events, compared to those on flare stars, are a natural consequence of inhomogeneous accretion since the rise-time is dependent on the length of an inhomogeneity in the flow, and thus any time-scale could be envisioned. It is also worth noting that the inferred areas and temperatures are consistent with a picture where the events take place in the same hot spot as implied by the long-term periodic variation of BP Tau.

Fig. 6 shows the rise-time (t_{rise}) and decay time to half the peak flux value ($t_{0.5}$) versus total energy in the U band for different flare stars according to Pettersen (1989). The events observed on BP Tau are shown as filled dots for time resolved flares and open dots for flares where either only the rise or decay time was observed. It is seen that the decay time is in line with what is observed on flare stars with corresponding flare energy, while the rise-time is preferentially much longer for BP Tau, showing the lack of an ignition phase on the TTS. Another difference between the events of BP Tau and flares on UV Ceti stars is their colours. According to Ishida et al. (1991) the average colours of the flares are (U-B)=-0.98±0.17 and (B-V)=0.05±0.13, to be compared to -0.5±0.1 and 0.5±0.1, respectively, for the events of BP Tau when transferred to the surface of an M dwarf.

Like in Paper I regarding the CTTS, we were surprised that also for BP Tau we did not detect a number of surface flares (a "bush"), regarding the sensitivity and time resolution of the present study.

7.2. *"Where is bush"*

No events with durations shorter than 0.6 hours were found and there is no significant power at frequencies corresponding to durations of less than 20 min, in particular the power is not more pronounced in the U band. If the TTS have surface magnetic activity similar to the flare stars, only the surfaces of TTS are larger, then we expect several surface flares to have been detected during our 135 hours of monitoring. Following Ishida et al. (1991), the frequency of flares occurring on UV Ceti stars is in the range 0.2−0.35 flares/hour. If these flares are evenly distributed on the stellar surface, then the corresponding frequency on a TTS would be about 5−10 flares/hour. We reach a limit of detection of rapid rises in flux of about 0.01^m in U and 0.008^m in B. These correspond to flare events on an M-dwarf with amplitudes of $> 0.75^m$ and $> 0.57^m$ in U and B, respectively. The majority of the UV Ceti flares have amplitudes in the range $|\Delta U| > 0.75^m$.

We conclude that *BP Tau shows no evidence of surface flares of the type frequently seen on flare stars*. Such activity should easily be detected in our survey, even considering that 1/2 of the surface of BP Tau could be hidden by a circumstellar disk. In Paper I evidence of powerful surface flaring was found for the WTTS studied, while there were indications that the CTTS lack such activity. It was speculated whether the magnetic configuration assumed for the polar accretion on a CTTS inhibits surface magnetic activity. Another possibility is that if the CTTS are slower rotators on the average than the WTTS as indicated by e.g. Bouvier et al. (1993) and Edwards et al. (1993), then the smaller dynamo effect on the CTTS could lead to a smaller surface activity on these stars compared to the WTTS. Support in this direction comes from the ROSAT survey by Neuhäuser et al. (1995) where a considerably larger fraction of WTTS are detected on X-rays, compared to the CTTS, although Feigelson et al. (1993) and Casanova et al. (1995) found no such differences from their ROSAT observations. Observations of the stellar activity of CTTS in X-ray will shred light on this question and in a following paper (Gullbring et al. 1995) we will present simultaneous optical and pointing ROSAT observations of BP Tau.

Considering now the distribution of the events discussed above and the striking lack of a tail of smaller and smaller events. It appears, at first sight, that the blobs of material accreting have a certain minimum size and a limited range in mass. We will now examine another possibility, however, where numerous small blobs contribute to the energy release.

7.3. *Accretion by a number of small fragments; shot-noise simulations*

In this picture we assume that the accretion flow is inhomogeneous and composed of a number of smaller fragments, each with a typical width and length. A fragment is defined by a cylinder with a characteristic radial extent and area smaller than the accreting surface of the star. Assuming further that the density distribution within such a cylinder is homogeneous, an individual fragment gives rise to a lightcurve with essentially a square shape. In the high-speed photometric data of BP Tau we see small-scale structures but no distinct square profiles. Therefore individual fragments are tiny.

We have performed shot-noise simulations of light curves of superimposed impulses. The parameters for the simulations were the mean frequency of occurrences, the time duration and amplitude of each event. All square profiles were assumed to be identical in order to minimize the number of free parameters in the simulations. We found that for square profiles of time durations of 7000 to a few 10^4 sec, amplitudes of the order of a few % of the Poisson noise and a mean frequency of 3 10^{-3} fragments per sec, brightness variations with the same properties as observed for BP Tau could always be produced. Both slow, soft and more rapid and sharply peaked brightenings result. Note that the amplitude of one square profile in the simulations is so low that it would not be possible to detect it in our observations, while the superposition of several profiles suffices to account for the observed variations *and the veiling*, very well.

We made a number of simulations corresponding to 100 hours of observations. Then we extracted a number of time-series with an observing window of 6.5 hours (corresponding to the length of a typical observing night) and found that, statistically, the simulated lightcurves are very similar to what we have observed for BP Tau, i.e. for ~80% of the simulated nights only slow or almost constant changes in the flux level occurred, while for <20% of the nights time-resolved events occurred. The light profile of an event could either be smooth or sharply peaked and they all result from the deposition and superposition of several infalling fragments. Also the "low-power" power spectra observed for BP Tau is reproduced. In Fig. 7 we show examples of shot-noised simulated "observations" over different "nights".

We also simulated other forms of light profiles, like triangular shapes or linear rises followed by exponential decays with shorter time durations. These profiles give more spikes than observed for BP Tau and smooth variations are unlikely unless a very high frequeny of impulses is choosed. In that case the power spectra of the simulations differ from what is observed on BP Tau in that they give too much power at higher frequencies and a flattening towards lower frequencies (reflecting the characteristic size of the impulses).

The steadiness of the excess temperature during a brightness variation of BP Tau is easy to explain in the model outlined. Each fragment produces an observable flux (assuming blackbody radiation) of

$$F_i \propto T_i^4 A_i / D^2, \tag{3}$$

where T_i and A_i are typical values of the temperature and the emitting area for each fragment and D is the distance to the star. If N such fragments are accreting at a certain time, then the total observable flux would be $F_{tot} = NF_i \propto NT^4A/D^2$ on the assumption that T and A are the same for each fragment on the average. Since the observed fluctuations of F_{tot} are

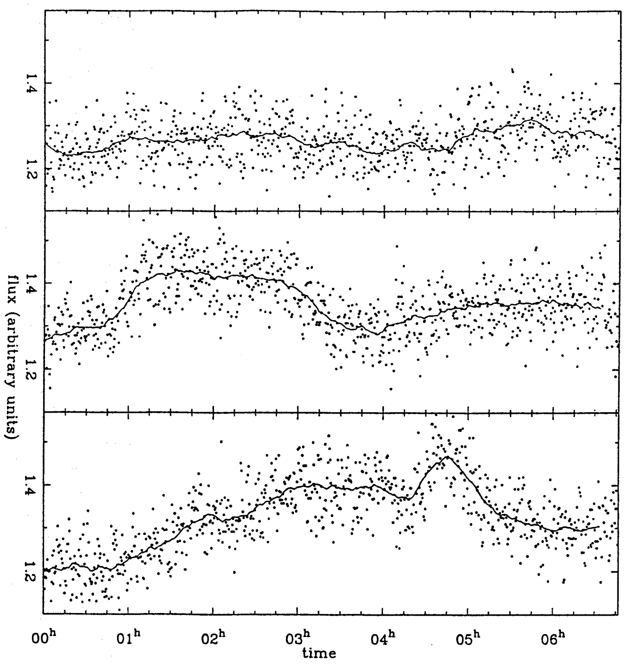

Fig. 7. Lightcurves, with time resolution of 30 sec, produced by shot-noise simulations of an inhomogeneous accretion flow (see text for details) with added Poisson noise to approach the observed situation. The upper panel shows a simulation with only low activity, the middle panel a slow, time-resolved event and the lower panel a fast event superimposed on slower variations. The solid lines show the binning (20 data points) of the simulated data for comparison with Fig. 1a.

due to changes in N, the temperature would remain essentially constant.

These shot-noise simulations do not imply that the presense of square-shaped profiles is conclusive, but rather that a shot-noised superposition of extended smooth pulses at a moderate frequency produces all observed properties of the brightness variability of BP Tau. Such extended pulses, together with the observed low temperature of the events (Section 5.1), are most easily interpreted in terms of fragmented accretion. It is worth noting that the presence of inhomogeneous accretion through a magnetosphere can lead to heating of the infalling gas in the magnetosphere (e.g. Scheurwater & Kuijpers 1988).

8. Conclusions

The classical T Tauri star BP Tauri has been reported to be very active, with pronounced short-term flare-like activity in addition to more regular long-term variability. The latter is confirmed by the present investigation in that we find a period of about 6.6 days. These cycles are best described by a hot spot or non-axisymmetric bright ring on the rotating star and the period is in line with, but not quite the same, as found by others. Our investigation provides new constraints on the character of the short-term optical light variability of this CTTS and we conclude:

1. There is no pronounced powerful flare activity on BP Tau. Most of the time the star is constant or varies only very slowly and smoothly in brightness, without any rapid events with residual total amplitudes of < 0.008 and 0.01 mag. in B and U, respectively.
2. Only a few distinct events (brightenings) with total amplitudes of 0.1 to 0.3 in the U band and with total durations of 0.6 to a few hours were observed over a total patrol time of 135 hours. One of these is flare-like, but only in the sense that it has a steep increase in flux followed by an exponential decline. The others have more or less the same rise- and fall-time, sometimes with rather complex small-scale oscillations.
3. All the events are "cool" in the sense as discussed by Gahm (1990) for "flares" on other CTTS and also demonstrated for VW Cha (Paper I). We show that when the underlying star plus the background veiling is subtracted, the temperature of the events at peak flux is only $7000 - 8000$ K. Hence, the events, including the one with a flare-like light profile, are very different from what normally is observed on flare stars.
4. The total optical energy released by the events range from 10^{35} to 10^{36} erg, with 10^{34} to 10^{35} erg only in the U band. There is a striking lack of events of lower energy and no time-resolved event has a duration of < 0.6 hours. By means of power spectra we have shown that there is no power at higher frequencies, in particular there is no power in the U band. The investigation shows that the events seen are not at the top of a distribution of frequent events of lower amplitude and short durations. In addition, there is no evidence at all in the light curves of a "bush" of spikes from surface flares. If this CTTS had a magnetic surface activity similar to the flare stars, then a number of flares would have been detected in the present survey. Similar indications were found in Paper I for the CTTS, while energetic flare-like events were observed on the WTTS. We speculate, that in some way the presence of a circumstellar disk, possibly in interaction with a stellar dipole field, inhibits the evolution of prominent surface flare activity and/or is related to weaker dynamo action because of slower rotation of the CTTS compared to the WTTS.
5. The events can most easily be understood as a result of inhomogeneous accretion from a disk to the star. We can not definitely conclude whether the accretion emission comes from a boundary layer or a hot spot, however the short time-scales favour models with magnetically controlled accretion. We investigate the energetics of this process, first under the hypothesis that the events are distinct blobs of material falling on to the star. The excess of material required over the normal steady mass infall is only about 10% in mass.
6. As a second hypothesis we assume that the mass accretion generally is very inhomogeneous and composed of numerous fragments that flow in a random way to the star. With simple, first order assumptions about these fragments we show that all aspects of light variability of BP Tau can be explained in this way. Most of the time the random flow of small fragments reproduces the veiling, which is constant or varies smoothly and slowly with time. During about 20% of the time the random flow produces distinct events with complex appearances, which should be compared to the 10% observed. These events, resulting from random clustering of fragments in time, have light curves which are indistinguishable from what is typically observed. One interesting aspect of this "fractal" model is that no change in temperature of the emitting region is expected during any change in brightness.

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