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Simultaneous optical and ROSAT X-ray observations of the classical T Tauri star BP Tauri*

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Abstract. The classical T Tauri star BP Tauri has been simultaneously observed with UBVRI high-speed photometry at a time resolution of 2 sec and with the ROSAT PSPC detector during five nights. BP Tauri showed brightness variations on time scales ranging from nights to hours both in the optical and in the X-ray band, however, the night-to-night variations in the optical and X-ray spectral regions were not correlated. On one occasion, a short term optical event with an amplitude in U of $\sim 0.05^{\mathrm{m}}$ and a time duration of 1.2 hours occurred, with no corresponding increase in the X-ray count rate during the decay of the event. In conclusion, the observations show that there are no detectable correlations between the optical and X-ray variability of BP Tau on time scales ranging from 1 hour to days. We discuss the possibility that the optical variability of BP Tau is related to accretion of circumstellar material onto the central star, while the X-ray emission presumably comes from magnetically active regions.

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

1. Introduction

T Tauri stars (TTS) are known to exhibit X-ray emission of considerable and variable intensity from the pioneering observations with the Einstein Observatory X-ray mission (see for instance Gahm 1981, Montmerle et al. 1983, Feigelson et al. 1988, Walter et al. 1988, Feigelson & Kriss 1989). With the launch of the ROSAT satellite, observations with higher sensitivity in both flux and spatial resolution could be achieved. Investigations of ROSAT surveys of the Chameleon I, Taurus Auriga and ρ Oph star forming regions have revealed an increased number of X-ray emitting young stellar objects (Feigelson et al. 1993, Casanova et al. 1995, Neuhäuser et al. 1995a and Neuhäuser et al. 1995b). The origin of the X-ray emission is not fully understood but is usually interpreted as arising from coronae and/or magnetic flare-like events. If the magnetic fields of TTS are generated by a dynamo process a relation between the rotation and X-ray emission would be expected. From ROSAT data of the Taurus Auriga star forming region, Neuhäuser et al. (1995a) found a correlation between the stellar rotational period and the X-ray surface flux. Feigelson et al. (1993) found no relation between the apparent rotational velocity ($v \sin i$) and the X-ray luminosity of TTS in the Chameleon I star forming region. Both authors found, however, strong relations between the stellar mass, radius, bolometric luminosity and the X-ray luminosity (see also Krautter et al. 1994).

TTS show pronounced activity in the optical with brightness variations ranging from less than one hour (flare like) to years. There are, however, differences in the properties of the optical flares between the two types of TTS (classified according to their equivalent width, W_α, of Hα; the weak lined T Tauri stars (WTTS) with $W_\alpha < 10$Å and the classical T Tauri stars (CTTS) with $W_\alpha > 10$ Å) in that the events on the WTTS have shorter rise times and are hotter than those on the CTTS (Gahm 1990, Gahm et al. 1995). The infrared (IR) excesses found for the CTTS indicate the presence of circumstellar disks around these stars. The distinction that CTTS have disks while WTTS do not is, however, spurious since there are a number of WTTS with low W_α but with IR-excesses. The increasing evidence that the CTTS are surrounded by circumstellar disks strongly indicates that the activity on the CTTS is related to accretion of material from such disks (see Guenther & Hessman 1993, Gullbring 1994, Gullbring et al. 1996 hereafter Paper I). It is still controversial whether the X-ray properties of WTTS and CTTS are similar or not. Feigelson et al. (1993) found no correlation between the X-ray flux and the strength of the Hα emission for different TTS while Neuhäuser et al. (1995a) found that WTTS have larger X-ray luminosities than CTTS and indications that the X-ray emission is harder for CTTS than for WTTS.

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Simultaneous observations in X-ray and optical of events on TTS can provide constraints on the underlying mechanisms responsible for the energy production. In particular, if the flare events are produced in magnetic loops as is believed to be the case for UV Ceti flare stars, a correlation between the optical and X-ray brightness variations should be expected. Only a very limited number of X-ray observations of TTS have been carried out simultaneously with other wavelength regions. Recently Feigelson et al. (1994) observed V773 Tauri (a WTTS) in X-ray (ROSAT), ultraviolet, optical and radio simultaneously during ∼8 hours. During what could be the decline of a radio-flare the star was constant in all other observed spectral regions. Since TTS rarely show fast variability in the optical (less than ∼5% of the observed time of these objects; Gahm 1994), simultaneous measurements should be performed over at least several nights to put constraints on the relation in the behaviour between different wavelength regions when the star is active. There is also only a limited number of patrol observations of single T Tauri stars solely in X-rays. Such measurements are important in order to trace the nature of the X-ray variability and to answer the question of whether the quiescent X-ray emission of T Tauri stars is due to the superposition of many flare-like events or to a more steady source like a coronae containing long lived structures. Time resolved observations have been carried out with the Einstein Observatory by for instance Feigelson & De Campli (1981) of DG Tau and SU Aur, Walter & Kuhi (1984) of AS 205 and AA Tau and with EXOSAT by Tagliaferri et al. (1988) of HD 560B (a Post-T Tauri star candidate). A recent investigation is the ROSAT observation of the CTTS LkHα 92 that was observed during 23 675 seconds (Preibisch et al. 1993). A huge X-ray flare was recorded, but no simultaneous observations at other wavelengths were made.

In this article we present five nights of simultaneous optical UBVRI and ROSAT PSPC monitoring of the CTTS BP Tauri. BP Tauri is typical for the CTTS class of TTS with IR-excess (Rucinski 1985). The optical short term variability of BP Tauri was extensively investigated in Paper I where it was found that the star normally exhibits smooth brightness changes on time scales of hours. Occasionally, short term events on time scales ∼1 hour occurred. EINSTEIN observations of BP Tau showed an X-ray luminosity of 1.15 10^{30} erg/s (Walter & Kuhi 1981) and from the ROSAT All-Sky Survey the luminosity was recorded as 0.7 10^{30} erg/s (Neuhäuser et al. 1995a). The optical variability raises the question of a possible short term variation in X-ray and its relation to the optical activity. The main goal of this investigation is to determine if the mechanisms behind the optical and X-ray activity are related or are of different origin.

2. Summary of observations

The observations of BP Tau (for the properties of BP Tau; see Paper I and references therein) were performed during five nights between September 10 to September 14, 1993. One of the five nights was clouded out and thus no optical data were taken. The optical observations were made at the 1.2 m telescope at the Calar Alto Observatory, Spain, with a fiber-fed

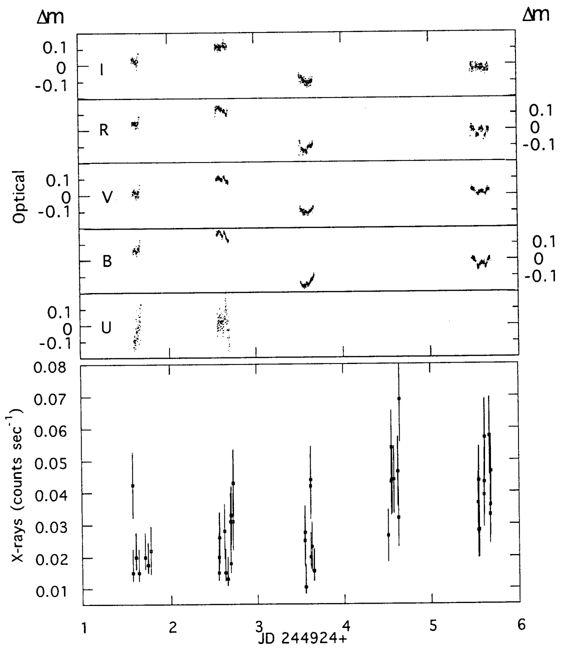

Fig. 1. Optical UBVRI light-curves (upper panels) and X-ray light-curves (lower panel) for the whole observing run. During and after the end of the second night the U-band channel of the instrument malfunctioned. The X-ray data are binned at 400 sec intervals and the error bars are set at the 68% confidence level.

fifteen channels three-star high-speed photometer (see Barwig et al. 1987) simultaneously in the Kron-Cousins U, B, V, R and I colours and with a time resolution of 2 seconds. Unfortunately the U-band channel malfunctioned during the last two and a half clear nights. The X-ray observations were made with the ROSAT satellite, using the Position Sensitive Proportional Counter (PSPC; Pfeffermann et al. 1987) for a useful observing time of approximately 29 ksec. The source counts were measured within a circle of radius 45″ around the target which was positioned in the center of the field. No nearby X-ray sources were located in the field close to the object, and source counts were recorded only at energies above 0.5 keV. This coupled with the low counting statistics of our data prevents any more detailed spectral analysis of our observations. The X-ray data were typically binned into time intervals of 400 seconds duration, and because of the low count rate no useful information on variability on shorter time scales can be derived. Note that the background count above 0.5 keV in a nearby control area was very low with 0 to 1 counts per 400 seconds bin, emphasizing that our data are photon-limited.

3. Statistical significance of the data and observational results

3.1. The optical data

The high-speed photometer measures the object, a comparison star and the sky simultaneously in all colors. Therefore the observational errors are dominated by photon noise, unless weather conditions are very unstable. Since we did not record any significant variability on time-scales of less than 1 minute, all the optical observations analysed in the following sections have been binned from 2 seconds to 50 seconds time resolution, with corresponding 1 σ errors of $\sim \pm 0.004$ in B, V and R and $\sim \pm 10.008$ in U and I.

During the observations BP Tau showed night-to-night variations in its brightness level in all colors. The total amplitude in the V-band of these variations was ~0.25 mag (see Fig 1, upper panel). On one night the star did also show short-term variations on time-scales less than hours. The details of these variations and their relation to the variations in X-ray are discussed in Sect. 3.3.

3.2. The X-ray data

In order to assess any variability in the recorded X-ray count rates we calculated the Poisson probability to record the observed counts in a given time bin for a single trial, given an assumed count rate level. This calculation was first performed on the data summed over each observing night in order to search for night-to-night variability. In a second step we repeated the calculation to search for variability on shorter time scales.

Let us first consider night-to-night variations. If we use the overall mean count rate r_{1-5} as reference level, we find the count rates too low during the first three nights, and count rates too high during nights four and five. A more reasonable hypothesis therefore appears to assume that the true quiescent level is defined by the mean rate of the first three nights r_{1-3}, while nights four and five represent highly significant upward excursions from this mean level. Of course, the alternate hypothesis that night four and five represent the true quiescent level and that nights one to three represent downward X-ray flux excursions is statistically also possible but physically less plausible. The results of our statistical analyses are summarized in Table 1; for each night we quote the recorded number of counts, the adopted count rate reference level and the probability to record at least the observed number of counts both for r_{1-5} and r_{1-3}. Obviously, if the overall mean rate is used as a reference level, one expects almost always to record more counts than observed during the first three nights, while for nights four and five the observed counts are extremely unlikely. If the mean rate for the first three nights is adopted instead as a reference level, nights 1 - 3 show no significant variability, while nights 4 and 5 showed enhanced count rates. At any rate we are forced to conclude that the observed count rate of BP Tau did exhibit nightly variations during our observations.

Next we investigated the individual observations separately and used as a reference level the observed mean count rate during each night. To this end we binned the X-ray data into contiguous 400 sec bins and compared the number of recorded counts with the expected number of counts. Since the ROSAT observations of BP Tauri were split up into individual observation intervals of about 1 - 1.5 ksec, i.e., non-multiples of 400 sec, we decided to retain any "left over" bins in excess of 300 seconds for analysis. Thus in total we have 63 such bins. We then looked for bins such that the probability to record at least the observed number of counts was no more than 0.02, and found two such events, one during the first night, and another one during the second night. Since this probability refers to a single trial, we have to fold in the total number of trials (i.e., bins). To find at least two events with a single trial existence probability of 0.02 in 63 trials, has itself a probability of 0.46. Thus - statistically speaking - we are forced to conclude that we have no hard evidence for short term (i.e, few hundred seconds) variability in the X-ray flux of BP Tauri. However, the event during the first night of our ROSAT observations, displayed in Fig. 4, does look very suggestive of a stellar flare; in this particular case two consecutive time bins show elevated count rates (16 recorded counts vs. 8.77 expected counts, and 12 counts recorded vs. 6.70 expected) and we therefore consider this event as real although it does not formally satisfy our criteria. A physical interpretation of this event will be presented in Sect. 5.

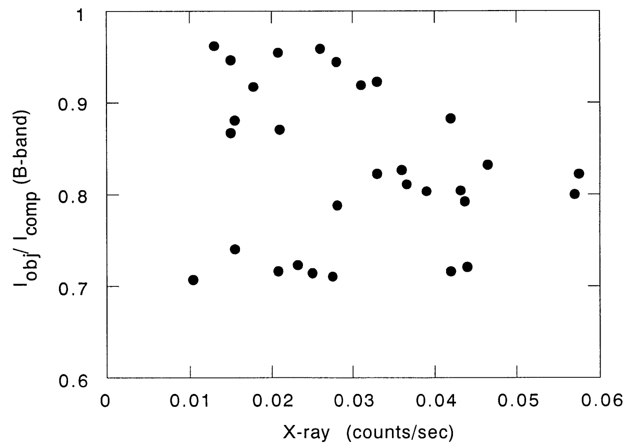

Fig. 2. Correlation diagram over the optical (B-band) and the X-ray brightness.

Table 1. Statistical significances for the variations in the nightly X-ray count rates. See text for details and definition of variables. Note that the different probabilities for nights 2 and 3 comes from the different distribution of counts in each night.

Night	Counts	r_{1-5} sec^{-1}	Prob.	r_{1-3} sec^{-1}	Prob.
1	122	0.033	0.99999	0.025	0.847
2	145	0.033	0.99997	0.025	0.5523
3	149	0.033	0.99775	0.025	0.1503
4	296	0.033	$1.36\ 10^{-13}$	0.025	$8\ 10^{-32}$
5	218	0.033	$3.72\ 10^{-3}$	0.025	$7\ 10^{-12}$

3.3. Relation between the optical and X-ray variability

We showed above that BP Tauri exhibited brightness variability in both X-ray and in the optical. Now we investigate if there exist any correlations between the variations in these two spectral regions. The maximum level in the X-ray count rates was observed during the fourth night of our observations. Unfortunately this

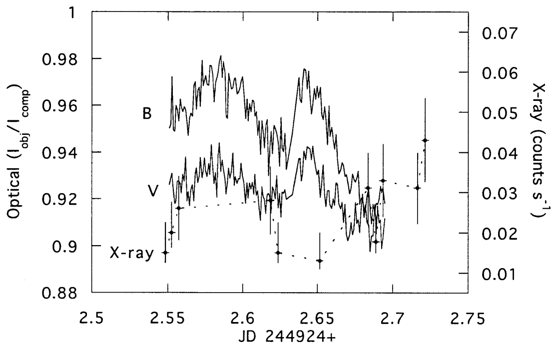

Fig. 3. An optically active night (JD 2449243) shown in the B and V-bands (solid lines) together with the corresponding X-ray count rates (dots). The optical data is smoothed by 100 sec. The U-band is not shown since this channel started to malfunction during this night.

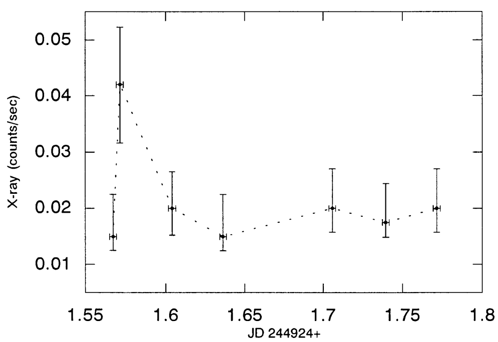

Fig. 4. A possible X-ray flare during the first night (JD 2449241) at a level just about significant.

night was clouded out so no simultaneous optical data was obtained. For the remaining four nights we binned the optical data with the same time resolution and observational window as the X-ray measurements (cf., Fig. 2). As can be seen in both Fig. 1 and Fig. 2, there is no correlation between the optical and X-ray level of the star at all. A formal correlation analysis resulted in a linear correlation coefficient for the data in Fig. 2 of 0.19 which occurs with a probability of 0.3 in uncorrelated data.

In Fig. 3 we plot the data of the second night of observation, where BP Tau revealed two events in the optical, clearly detectable in all photometric bands. The amplitude of the second bump in Fig. 3 was $\sim$0.036^{m} in V and $\sim$0.045^{m} in B with a time duration of $\sim$1.2 hours. Data from the U-channel is not shown in Fig. 3 since the channel started to malfunction during this night. It was, however, possible to recover a U-band amplitude of the event of $\sim$0.05^{m}. The energy of the excess flux of the optical flare was a few times 10^{34} ergs. From Fig. 3 it is also apparent that the simultaneous X-ray observations showed no significant increase in the count rates neither during the decay phase nor after the time of the optical event and therefore we conclude that the optical event had no counterpart in soft X-ray emission. Thus, within the limits of our observations, the brightness changes of BP Tauri in the soft X-ray and in the optical of time duration spanning from days to $\sim$1 hour occurred without any correlation.

4. Origin of the optical and X-ray variability

Accretion induced activity leads to optical variability while magnetically induced variability leads to correlated optical and X-ray variability such that the ratio between the radiated energies at optical and X-ray wavelengths are of the order unity. Furthermore, magnetically active regions on the stellar surface are expected to be close to cool spots thus corresponding phenomena should be correlated with stellar rotation. Do we find evidence for either behaviour in our data?

It is not possible from our five nights of observations to determine if the nightly X-ray variability is connected to the stellar rotation. It is worth noting that the X-ray light curve is consistent with the previously observed stellar rotational period of BP Tau of 6.1- 8.3 days (Vrba et al. 1986, Simon et al. 1990, Shevchenko et al. 1991, Richter 1992 and Paper I), but it is more difficult to fit the night-to-night variations in the optical data to a period longer than $\sim$5.5 days. There is no trend in the data indicating higher X-ray fluxes when the star is in a lower optical state (Fig. 2). If BP Tau contains magnetically active regions on the stellar surface, they are expected to be related to areas close to cool spots on the surface and the star would then show an enhanced X-ray activity when the star is faint. This should also be seen in the optical, especially in the U and B-band. No such anti-correlation between the optical activity and the mean brightness of BP Tau is seen during this or in previous observations of the star (Paper I).

The optical flare observed during the second night had an amplitude of only 0.05^{m} in the U-band. Since BP Tau has a radius of $\sim$2.5 $R_{\odot}$ and an effective temperature of 4000 K (Bertout et al. 1988, Gullbring 1994) as compared to 0.3$R_{\odot}$ and 3300 K for UV Ceti type flare stars (e.g. Pallavicini 1990) the same event would have appeared as a very pronounced flare with an amplitude $\sim$1.9^{m} on an M-type flare star. Using our optical BVRI data we determined the temperature of the flare event after subtraction of the spectrum from an underlying K7 star as $\sim$6600 K, which is in line with temperatures found previously for events on BP Tauri. This temperature is lower than what is normally observed for flares on dMe stars. We estimated the X-ray luminosity by assuming a temperature and emissivity of the X-ray emitting plasma and by computing the interstellar X-ray absorption from the observed optical extinction. Since the X-ray spectra of TTS are consistent with temperatures of $\sim 10^{7}$ K (Montmerle et al. 1993) we assumed this temperature together with an isothermal hot plasma for the X-ray emission of BP Tau. An adopted optical interstellar extinction towards BP Tau of A_V=0.65 yields a column density of absorbing atoms as $A_V \times 1.5\ 10^{21} = E 10^{21}$ cm^{-2}. Under these assumptions the quiescent X-ray level, during the last part of the first night and the second night, corresponds to a luminosity of about 5 10^{29} erg/s for a distance of 140 pc to BP Tau (using the energy conversion factor for the PSPC detector as given by Neuhäuser et al. 1995a). These estimates of the X-ray luminosities are considerably lower than the corresponding optical luminosities. For instance, during the optical event of the second night the peak luminosity was $\sim 5\ 10^{31}$ erg/s. Because no enhancement in the X-ray count rate was observed, a limit on the fraction of flare energy emitted as observable soft X-ray can roughly be estimated as less than a few percent of the optical emission. For flare stars the ratio between energies in the optical and X-ray regions are typically 0.1 to 1 (Byrne 1989). Since the total energy released in the optical flare of BP Tau was a few times 10^{34} erg one should expect an observable increase in the X-ray count rate if the flare was similar to what is observed for flare stars.

The appearance of the tentative short-term X-ray event observed on night 1 (see Sect. 3.2 and Fig. 4) is reminiscent of the flares observed on dMe flare stars. Since the X-ray data was binned into 400 sec intervals we could not estimate, for instance, the decay time with a high accuracy. The rise and decay time, however, are consistent with values of <5 minutes and ~ 40 minutes (to the approximate $1/e$-level), respectively. Unfortunately no simultaneous optical data was obtained for the event but the morphological similarity of this X-ray event to the flares observed on flare stars strengthens the idea that at least some of the X-ray emission arises in magnetically active regions.

In Paper I it was proposed that the optical variability, even on short time-scales, are due to the accretion of circumstellar material onto the stellar surface. It is possible to produce X-ray emission from an accretion shock if the inflow of the accreting material is magnetically controlled (Gullbring 1994), but the rather low gravitational potential of T Tauri stars would typically limit the hardness of the arising X-ray emission to below 0.5 keV, and would thus only contribute to the X-ray emission at very low energies.

Optical variability caused by variable accretion can be very energetic. A change in the accretion rate of only a few percent is sufficient to produce variations in luminosities of more than 10^{31} erg/s (see Paper I). Flux variations in the optical caused by the release of magnetic energies (as for solar-type flares) would then be heavily masked by the accretion-induced variations. It is possible that if the optical events as well are produced by the release of magnetic energy, then the corresponding X-ray emission would be very weak and/or absorbed in the energy process. However, the lack of a corresponding increase in the optical activity when the X-ray count rates increases, as observed during the third and especially the fifth night is difficult to envision in this context. One possibility is that the X-ray emission is not produced close to the stellar surface, as for localized stellar flares, but instead arises in magnetic regions further out from the star like in a dipole magnetosphere. Since for CTTS such a magnetosphere would interact with the circumstellar disk, complex magnetic field configurations would be expected and release of magnetic energy would certainly occur (see for instance Aly & Kuijpers 1990, and the discussion by Feigelson et al. 1994). In that case it would be possible to have variable X-ray radiation far from the stellar surface without corresponding optical emission.

5. Conclusions

We have observed the classical T Tauri star BP Tau simultaneously with optical UBVRI high-speed photometry and with the ROSAT PSPC detector during five nights. The results of this investigation can be summarized as:

1. BP Tau reveals brightness changes in X-ray on a night-to-night basis. It is not possible from this investigation to tell whether the X-ray variability is connected to the rotation of the star or if the X-ray emission is intrinsically variable.
2. The optical brightness level did also change on a night-to-night basis in all photometric bands. However, the variation was not correlated to the variation in X-ray flux. We thus conclude that the sources responsible for the nightly X-ray and optical variability of BP Tau are not related.
3. During one night we observed a fast low amplitude optical event on BP Tau with amplitudes of $<0.05^{\rm m}$ in U and $\sim 0.045^{\rm m}$ in B lasting for ~ 1.2 hours. The simultaneous X-ray measurements did not reveal any increase in count rate during the optical event. This strongly suggests that even the rare fast events observed on BP Tau (see for instance Paper I) are produced in different regions than what is the case for the X-ray emission which differs from what is observed on flare stars.
4. On one night a short duration X-ray flare was observed with a rise time of <5 minutes and a decay time (to the approximate $1/e$-level) of ~ 40 minutes. Unfortunately no simultaneous optical observations are available, however the similarity of this event to the flares observed on dMe flare stars strengthens the idea that the X-ray variability is related to magnetically active regions on the stellar surface.

We propose that the mechanisms behind the observed optical and X-ray variability are different. Presumably the major part of the optical variability is produced by variable accretion while the X-ray variability is related to magnetically active regions which only cause a low level optical activity that is overwhelmed by the accretion-induced variations. This strengthens the idea that the optical variability, even on shorter time-scales, is produced by accretion phenomena. Similar multi-wavelengths observations of WTTS should give other relations between the optical and X-ray activities.

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