A&A manuscript no.
(will be inserted by hand later)

Your thesaurus codes are:
08(08.02.3;08.03.4:08.06.2:08.16.5:02.01.2)

ASTRONOMY
AND
ASTROPHYSICS

Accretion in Taurus PMS binaries: a spectroscopic study *

G. Duchêne[1], J.-L. Monin[1,2], J. Bouvier[1], and F. Ménard[1,3]

[1] Laboratoire d'Astrophysique, Observatoire de Grenoble, Université Joseph Fourier, BP 53, 38041 Grenoble Cedex 9, France
[2] Institut Universitaire de France
[3] Visiting Astronomer at CFHT

Received; accepted

Abstract. We present low-resolution optical spectra of each component of 10 T Tauri (TT) binary systems with separations ranging from $0\farcs9$ to $3\farcs5$ and located in the Taurus star-forming region. We derive the spectral type and Hα equivalent width of each component.

Complementing these results with those of Monin et al. (1998), yields a sample of 14 binaries and one triple systems, with resolved optical spectroscopy. We find that mixed binaries (CTTS+WTTS) are rare, representing only 15–20 % of the systems in the separation range of $0\farcs8$ to $3''$. Supplementing these results with those of Hartigan et al. (1994) and Prato & Simon (1997), we show that the tendency of binary TTS to be twins holds to separations up to $13''$. This is unlikely to be the result of random pairing, and confirms previous results that both stars in young binaries accrete over the same time period.

In binary systems where both stars are still accreting, our measurements show that the most massive star is usually the component with the largest accretion rate by up to a factor of 10, as determined from the Hα luminosity.

Key words: binaries: general – circumstellar matter – stars : formation – stars : pre-main sequence – accretion, accretion disk

1. Introduction

During the past five years, many studies have addressed the issue of multiplicity in low mass star-forming regions. A majority of G-K main sequence (MS) dwarfs belong to multiple systems in the solar vicinity (Duquennoy & Mayor 1991), and several studies (Leinert et al. 1993, Reipurth & Zinnecker 1993, Ghez et al. 1993, Simon et al 1995) have shown that this is also the case among pre-Main Sequence (PMS) stars. The binary fraction can vary with star formation region (SFR), and in the Taurus cloud, the binary excess over MS stars is of order of 1.7, indicating that binarity is a fundamental feature of stellar formation, at least in this SFR (see Duchêne, 1999).

Amongst the various mechanisms proposed so far for binary star formation, fragmentation appears as the most likely to meet observational constraints (Boss 1993). Numerical codes have been successful in reproducing the formation of binary or multiple systems (Bonnell et al. 1992, Sigalotti & Klapp 1997ab, Boss 1997, Burkert et al. 1997). However, current binary formation codes do not offer enough resolution and time span to follow the formation and evolution of circumstellar accretion disks. Only larger structures, not necessarily in equilibrium, are predicted, providing indirect information about these disks, but the fate of the available circumstellar matter remains unclear.

Various authors have studied tidal interaction of circumstellar disks in binary systems for coplanar disks (see a review by Lin & Papaloizou 1993), and demonstrated that Lindblad resonances create a gap in the binary environment, separating two circumstellar disks from a circumbinary one. Accretion from the outer disk onto the inner ones and, eventually, on both stars is prevented by gravitational resonances. However, Artymowicz & Lubow (1996) showed that, under some hypotheses on the disk properties, matter could flow through one or two points of the inner ring of the circumbinary disk toward the central system. If both stars have similar masses, both circumstellar disks are replenished, while, in the case of very unequal masses, the accretion funnel is mainly directed toward the *secondary*. On the other hand, Bonnell et al. (1992) used a SPH code to study cloud fragmentation processes and concluded that fragmentation of an elongated cloud rotating around an arbitrary axis leads to parallel but non-coplanar accretion disk like structures. They find that, in low mass ratio systems ($q \ll 1$), accretion of low angular momentum material is directed toward the centre of mass, which is close to the most massive star. Thus, in these systems, the *primary* appears more obscured and reddenned than its less active companion. The different conclusions about the more actively accreting star

Send offprint requests to: G. Duchêne, Gaspard.Duchene@obs.ujf-grenoble.fr

* Based on observations made with the Canada-France-Hawaii Telescope, operated by the National Research Council of Canada, the Centre National de la Recherche Scientifique de France and the University of Hawaii are due to the different approaches used in these studies: while Artymowicz & Lubow (1996) start with a star+disk system to which they add a second star, Bonnell & Bastien (1992) model the formation of such a binary from the onset of the gravitational collapse. Also, the different initial conditions used in these two studies imply different angular momentum values for the accreting material (see Bate & Bonnell 1997)

The study of accretion activity on both components in PMS binary systems brings insight into the way the residual matter flows onto the central stars. This activity can be traced by spectroscopic measurements. However, up to now, such studies on PMS binaries in Taurus have been limited to wide systems (Hartigan et al. 1994, hereafter H94) due to the limited spatial resolution of the observations. Monin et al. (1998, hereafter paper I), have started a spectroscopic survey of wide young binaries in Taurus. In this paper, we extend this study to closer systems (down to $0\farcs9$), investigating the classification as classical (C) or weak-line (W) TTS of both stars in these binaries, along with a more detailed study of the spectroscopic signature of their accretion activity. We restrict ourself to the Tau-Aur association and we complement our results with those of H94 and Prato & Simon (1997, hereafter PS97) to extend this study to a wider range of systems.

In section 2, we present the observations, and the data reduction process. The results and the classification of individual stars as C/W TTS are presented and discussed in section 3, and an evaluation of the random pairing hypothesis is presented in section 4. The accretion activity of each component within binaries is compared in section 5. A discussion and a summary are presented in section 6.

2. Observations

2.1. The sample

We have chosen our sample from the list of Mathieu (1994). Monin et al. (1998) have already obtained spectroscopic measurements on five objects in this list, with separations ranging between $2\farcs4$ and $5\farcs9$. In this paper we present complementary observations of closer binaries from the same list. This new sample (see Table 1) now includes all the binaries in this list with separations ranging between $0\farcs89$ and $3\farcs1$, to the exception of HBC 411 (CoKu Tau/3) and HBC 389 (Haro 6-10).

2.2. New spectroscopic observations

The observations were conducted on 1996 November 5 and 6, and December 1st, at the CFH Telescope on Mauna Kea. We used the STIS2 2048×2048 detector with a $0\farcs16$/pixel scale. Using SIS (Subarcsecond Imaging Spectrograph) providing tip-tilt correction, we obtained an angular resolution of about $0\farcs6$ to $0\farcs8$. Differential VRI imaging photometry was also performed during the first two nights for some targets. For each system, the primary has been defined as the brightest star in the V band.

Table 1. Complete list of spectroscopically observed binaries (paper I and this paper). Listed are the Herbig & Bell (1988) catalogue numbers (hereafter: HBC) of the primaries and secondaries when available, the separation and the previous classification of the whole systems as CTTS or WTTS (HBC).

HBC	object	ρ ($''$)	TTS
356–357	NTTS 040012+2545 S–N†	1.33^a	W
358	NTTS 040047+2603 W	1.6	W
379	LkCa 7†	1.1	W
	J 4872†	3.5	W^b
43–42	UX Tau AB*	5.9	WW
43	UX Tau AC*	2.7	W
44	FX Tau†	0.9	C
45	DK Tau*	2.8	C
48	HK Tau*	2.4	C
	GG Tau/c†	1.4	–
57	GK Tau†	2.5	C
60	HN Tau*	3.1	C
	IT Tau†	2.4	C^b
73–424	Haro 6-37*	2.7	CC
76	UY Aur	0.9	C
80	RW Aur†	1.5	C

† resolved VRI imaging photometry was obtained for these objects
* paper I
^{a} this work
^{b} Hartmann et al. (1991)

Long-slit spectra were obtained using a $1''$ slit and a grism. The usefull range of the spectra is 4000 to 7800 Å, yielding a 1.8 Å/pixel scale. However, the actual resulting spectral resolution is 9.6 Å, except for HBC 356–357 where it is 12.5 Å. Spectra of calibration lamps and of a spectrophotometric standard (Feige 110) were obtained every night. All spectra have been wavelength calibrated, cosmic-ray cleaned, flat fielded, sky emission subtracted and flux calibrated. All data reduction steps were performed with standard IRAF[1] routines. The primary and secondary spectra of each binary were deblended and extracted using a task fitting two gaussians with the same FWHM profile. This reduction procedure is accurate as long as the separation remains larger than the seeing, which was the case for all our sources except FX Tau and UY Aur, the closest systems of our sample (see section 3.1 for details).

Our estimates of the spectral types are based on the strength of TiO bands for M stars, and on relative strengths of Ca I $\lambda\lambda$6122,62, Na I $\lambda5893$, CaH $\lambda\lambda$6350,80 and CaH $\lambda\lambda$6750–7050 for K stars. We used the standard grids from Allen & Strom (1995) and Kirkpatrick et al. (1991), and we also observed a series of spectral type standards during the same nights as the binary targets. From these standard stars measurements, we find that our estimates are accurate to within one subclass for the whole sample. However, we are unable to determine

[1] IRAF is distributed by the National Optical Astronomy Observatories, which is operated by the Association of Universities for Research in Astronomy, Inc., under contract to the National Science Foundation

spectral types later than M5, because all features then become almost constant in this spectral range. Spectra at longer wavelengths are needed for the classification of the reddest objects.

Uncertainties on emission line equivalent widths (hereafter EW) were estimated by using the maximum and minimum acceptable continuum values next to the lines. They are typically smaller than 5%, except for the weakest lines, where they are of the order of 0.1–0.2 Å. In the blue part of the spectrum, for the faintest stars, uncertainties can reach 10–15%.

We evaluated differential photometry for 8 of our sources in the VRI bands. Uncertainties are usually smaller than 0.02 mag and never exceed 0.03 mag.

3. Results

The spectra are shown in Figure 1 and the corresponding results are summarized in Table 2, with the relative photometry given as $\Delta M = M_B - M_A$. For some objects, we could also detect Hγ , Hδ , [O I]$\lambda 6363$ and the [S II]$\lambda\lambda$6716,31 doublet in emission (see Appendix A).

3.1. Comments on individual binaries

The spectral type of GK Tau B could not be determined due to a poor signal-to-noise ratio but does not show strong TiO absorption bands. The spectral type of RW Aur A is undetermined from our spectra because the star is heavily veiled by a hot continuum and does not show any photospheric feature ; higher resolution spectra are needed to assess its spectral type, see Basri & Batalha (1990) or Chen et al. (1995).

UY Aur is one of the closest binary of our sample, leading to a possible contamination of the secondary's spectrum by the primary's. We have checked this point by performing careful cuts through the UY Aur spectrum perpendicular to the dispersion axis. These cuts show a systematic asymmetry, which position does not change with wavelength and is not observed on the primary of any other system, even with the same slit position angle. Furthermore, the separation we infer from the spectra ($0\farcs90 \pm 0\farcs05$) is fully consistent with the result of near-infrared imaging (Close et al. 1998) and the resulting secondary spectrum displays different spectral features than the primary.

In the case of FX Tau, the raw spectrum clearly shows two separated peaks, but they are very close (the seeing was about $0\farcs8$ FWHM). The double gaussian fitting procedure was unsuccessful, and we had to apply a line by line deconvolution process. The seeing is slightly better at longer wavelength and we could retrieve both components in this part of the spectra only. They show significantly different features, so we believe we have resolved the system. This is enough to measure the Hα emission and to estimate the spectral type, though with a larger uncertainty (2 subclasses).

Optical spectra of the GG Tau/c binary were obtained by White et al. (1999), who found spectral types M5 and M7 for the primary and secondary, respectively. This is in agreement with our findings for both components, although we could not determine accurately the spectral type of the secondary.

We have also determined an accurate estimate of the separation of HBC 356–357: $1\farcs33 \pm 0\farcs05$. Walter et al. (1988) reported a somewhat larger separation ($2''$). However, these authors did not publish the uncertainty on their result, and we believe that this discrepancy is unlikely to be due to orbital motion.

In order to study the relative accretion activity of the individual components of the binaries of our sample, we first determine which stars actually accrete, ie., the respective classification of the observed binaries as CTTS or WTTS. In the following, we use every available bit of information to establish this classification.

3.2. TTS classification criteria

The first large scale surveys for TTS were objective prism surveys and the "historical" criterion to detect a CTTS used the Hα EW by checking wether it was larger than 10 Å or not (e.g., Strom et al. 1989). The stars identified as TTS from their photometry, but with smaller Hα EWs were classified as WTTS, i.e., non-active PMS stars. However, this threshold is not a sharp edge, and a more physically meaningful diagnosis would be the Hα flux (Cohen & Kuhi, 1979). Moreover, Martín (1998) showed that the Hα EW threshold varies with spectral type, later spectral types stars having a higher threshold. He proposed a 5 Å EW limit for K stars and 10 Å for early M stars. We adopt this latter criterion.

We have also checked this classification against other criteria such as [O I]$\lambda 6300$ emission line and $K-L$ infrared excess. Edwards et al. (1993) have found that stars with detectable [O I] emission and $K-L$ excess (> 0.4) have Hα EW larger than 10 Å.

However, in order to compare of our newly classified TTS with previously known field TTS, the use of different criteria may lead to confusion and unexpected biases. This point will be carefully examined below (see section 4.2), but it is worth stressing that only one star out of the 31 listed in Table 2 has a discrepant classification when using different criteria (see also section 4.2.1).

3.3. Classification of individual stars

NTTS 040012+2545, NTTS 040047+2603, LkCa 7 and J 4872: no components in any of these systems show evidence of accretion activity, and they exhibit only low Hα emission and no other emission line, to the exception of HBC 358. These four systems are thus considered as WW binaries.

GK Tau, IT Tau, UY Aur, and RW Aur: all these systems contains stars with moderate to strong Hα and Hβ emission and, for some of the stars, metallic and forbidden lines. All the stars in these systems can thus be safely classifed as CTTS.

FX Tau: the secondary shows a very low Hα emission and is probably a WTTS. On the other hand, the primary shows a

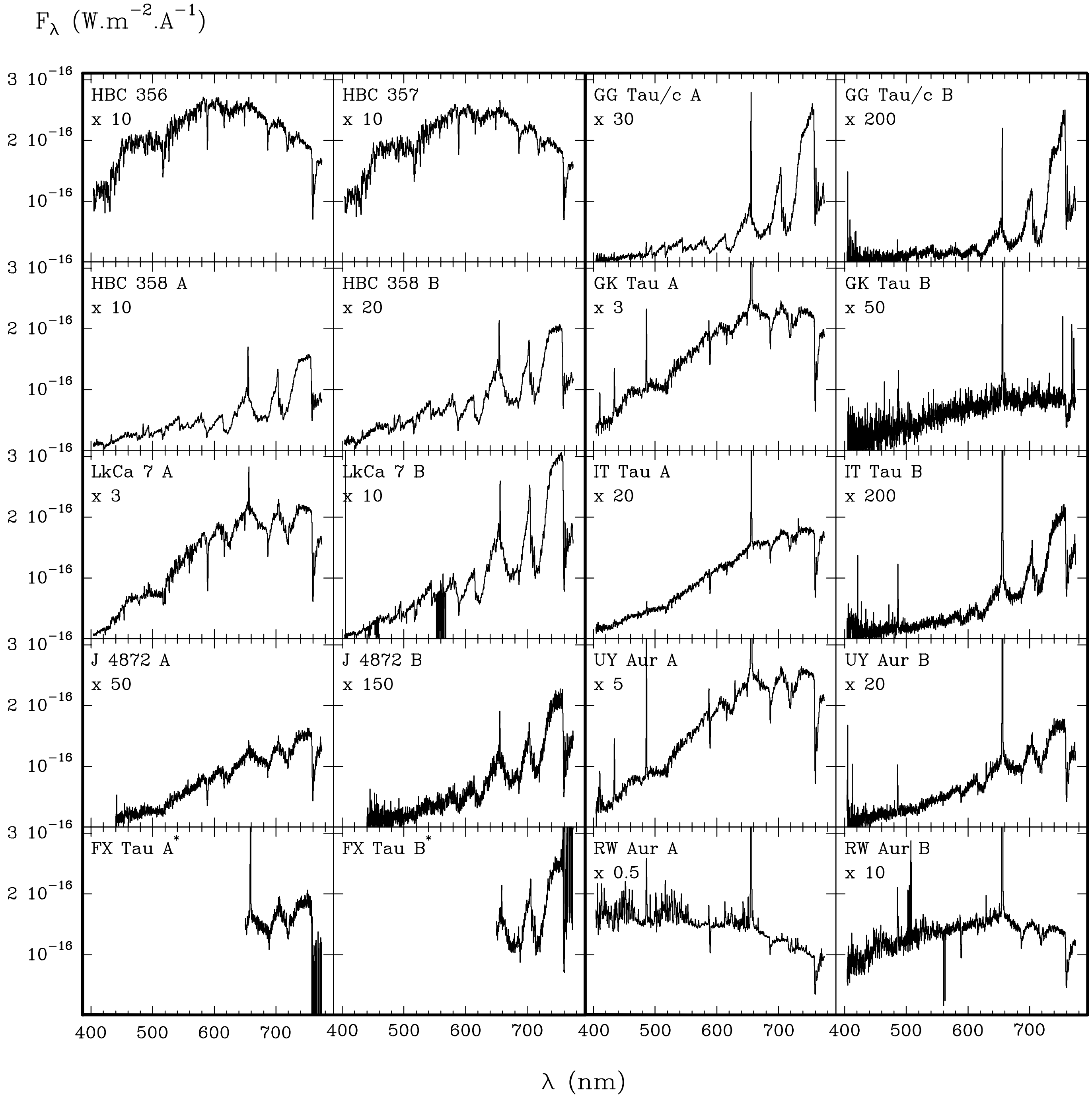

Fig. 1. F_λ spectra for all components of our study. The ordinate range is fixed for all stars, and spectra have been scaled for convenience. Parts of the spectra with errors in gaussian fitting are not shown (exceptions are a small range around 5600 Å for LkCa 7 and the reddest part of FX Tau spectra, around 7600 Å). * FX Tau spectra are not flux calibrated, due to the deconvolution procedure (i.e., the vertical scale is arbitrary).

moderate emission in this line, as well as Hβ emission (Cohen & Kuhi 1979). Also, Strom et al. (1989) and Skrutskie et al. (1990) reported moderate ΔK and ΔN excesses for the system. All these evidences support the idea that the primary is a CTTS.

UX Tau & HK Tau: UX Tau A was observed in paper I and classified as a WTTS from its Hα EW of 9.5 Å. In such a star apparently "at the border" between C and WTTS, we reexamined this classification and propose to (re)classify it as a CTTS, because of the large corresponding Hα emission flux (for a spectral type K4, the CTTS threshold is more of the order of 5 Å). Another clue is its significant ΔN excess (Skrutskie et al. 1990). This post facto reconsideration of classification criteria can be misleading at first sight, but we stress that it is only done here to define a more accurate picture of an accreting TTauri star. The classification of all other stars is identical

Table 2. Photometric and spectroscopic results for stars in our sample. "–" means that the line is undetected in our spectra. The relative photometry given in parentheses was obtained from our spectra (see section 5). No emission line has been measured in the spectrum of FX Tau at wavelengths shorter than 6500 Å. The last column present our classification of the stars: "W" for WTTS and "C" for CTTS (see text for details).

HBC	object	spec. type	ΔV (mag)	ΔR (mag)	ΔI (mag)	Hα EW$_\lambda$(Å)	Hβ EW$_\lambda$(Å)	[O I]$\lambda 6300$ EW$_\lambda$(Å)	He I $\lambda 6678$ EW$_\lambda$(Å)	type
356	NTTS 040012+2545 S	K3	0.07	0.08	0.06	0.4	–	–	–	W
357	NTTS 040012+2545 N	K3	(0.1)	(0.0)		0.4	–	–	–	W
358	NTTS 040047+2603 W A	M5				10.0	8.7	–	–	W
	NTTS 040047+2603 W B	M5	(0.3)	(0.3)		6.7	6.0	–	–	W
379	LkCa 7 A	K9	2.18	2.03	1.03	2.5	–	–	–	W
	LkCa 7 B	M4	(2.0)	(1.8)		5.6	–	–	–	W
	J 4872 A	K9	1.50	1.40	0.83	0.8	–	–	–	W
	J 4872 B	M1	(1.7)	(1.5)		4.2	–	–	–	W
44	FX Tau A	M1	0.24	0.30	-0.10	13			–	C
	FX Tau B	M4				1.0			–	W
	GG Tau/c A	M5	2.74	2.57	2.13	22	15	–	–	C
	GG Tau/c B	>M5	(2.6)	(2.5)		19	39	–	–	C
57	GK Tau A	K7	4.26	4.20	4.10	35	13	–	0.3	C
	GK Tau B	–	(4.1)	(4.1)		45	11	–	–	C
	IT Tau A	K3	3.63	3.15	2.27	21.7	3.4	–	–	C
	IT Tau B	M4	(3.6)	(3.2)		147.	52.	0.3	0.7	C
76	UY Aur A	K7				86.	29.	1.5	0.8	C
	UY Aur B	M2	(2.7)	(2.5)		69.1	33.8	3.8	–	C
80	RW Aur A	?e	4.36	3.85	3.25	76	7.9	1.1	1.3	C
	RW Aur B	K5	(3.4)	(3.2)		42.7	7.3	2.1	0.3	C
				Data from paper I:						
43	UX Tau A	K4				9.5	–	–	–	C
42	UX Tau B	M2	(2.4)	(2.2)		4.5	3.5	–	–	W
	UX Tau C	M3	(4.0)	(3.9)		8.5	–	–	–	W
45	DK Tau A	K9				31.	16.	2.5	0.7	C
	DK Tau B	M1	(1.7)	(1.6)		118.	33.5	4.8	1.5	C
48	HK Tau A	M1				50.	20.	–	–	C
	HK Tau B	M2	(2.6)	(2.7)		12.5	–	–	–	C
60	HN Tau A	?e				230.	64.	16.	2.5	C
	HN Tau B	M4.5	(3.8)	(3.7)		65.	41.	8.	2	C
73	Haro 6-37 A	K8				19.5	3.7	–	–	C
424	Haro 6-37 B	M0	(1.4)	(1.2)		195.	60.	–	–	C

to paper I. In particular, our previous classification of HK Tau B as a CTTS (Hα EW of 12.5 Å) has been recently confirmed by an HST image of this star showing a remarkable edge-on circumstellar disk (Stappelfeldt et al. 1998).

4. CTTS - WTTS pairing within Taurus binaries

In the following, we call "twins" the systems where the TTS are of the same type (either CC or WW), and "mixed" the systems where the stars are different.

One of our objects contains stars physically associated in a multiple system (UX Tau). Although this system is not strongly hierarchical ($5\farcs9$ - $2\farcs7$), we consider that this system can be split into "independent" binaries, leading to a total of 16 binaries in our sample. The validity of this assumption will be evaluated in Section 4.2.4.

4.1. Testing the random pairing hypothesis

The 16 binaries considered here can be divived into three categories: 9 binaries contain only CTTS ($\approx 56\,\%$), 4 binaries are formed of two WTTS (25 %), and 3 binaries are mixed (all with a CTTS primary, two of them in the same triple system, UX Tau), representing less than 19 % of mixed systems. Mixed systems appear to be rare in TTS binaries, and this is even more striking when we use the "historical" Hα $10\,$Å EW criterion. Then only one mixed system remains among 16 binaries, making the proportion of the order of 6%. We use this sample to address the question: are binary components taken at random from the TTS population?

If we want to compare this result with a distribution randomly taken from a single TTS population, we need to know the ratio of WTTS-to-CTTS in Taurus. In a study limited to the central parts of the Tau-Aur dark cloud, Hartmann et al. (1991) found a ratio close to unity. Considering a larger sky area leads to an even larger WTTS-to-CTTS ratio, mainly because of the widespread $ROSAT$ population (e.g., Wichmann et al. 1996). Walter et al., 1988). Since our sample mostly contains systems in the center of the molecular cloud, we conservatively adopt a W/C ratio$=1$.

Taking a fixed distribution of primaries (4 W & 12 C), the probability to get 3 mixed systems out of 16 binaries from randomly taken secondaries is $\mathrm{C}_{16}^{3}(\frac{1}{2})^{16} \leq 1\,\%$. We therefore reject the hypothesis that components of TTS binaries are randomly associated from the single stars distribution. In other words, the TTS types of Taurus binary components are significantly not independent.

4.2. Possible sources of bias

In this section, we discuss some possible sources of errors in our result on a preferential CC pairing in TTS binaries.

4.2.1. The use of different classification criteria

In section 3.2, we have used complementary criteria to establish the C/W TTS nature of our sources. However, considering only the "historical" $10\,\text{Å}$ Hα EW classification criterion does not only imply minor changes (1 star in UX Tau upon 31 is modified), but makes mixed binaries even more rare: only one mixed pair (FX Tau) out of 16 remains. The probability that the observed C/W distribution in our 16 binaries results from random pairing then falls to $\approx 0.02\,\%$.

4.2.2. The case of WW pairs

The evolutionnary status of the WTTS population identified from the $ROSAT$ All-Sky Survey is somewhat uncertain: some of these stars may be unrelated to the TTS population (Favata et al. 1997). For instance, if they are young main sequence stars, we expect that both components will mimic WTTS since they are too old to still be accreting. Then the observation of such binaries can lead to a bias towards WW pairs in our study. This can potentially affect 2 binaries in our sample, first detected by $ROSAT$ (named after "NTTS"). If we exclude *all* WW binaries for safety, we end with at most 3 mixed systems out of 12, yielding a proportion of 25 % mixed systems in TTS binaries. Then the probability that this distribution results from random associations is only $\approx 5\,\%$. We therefore conclude that the high proportion of twin binaries in our sample is not strongly affected by the presence of spurious WW binaries.

4.2.3. Time evolution

Since the proportion of stars surrounded by a circumstellar disk decreases with age, we inspect the possibility that our binary population is younger, on average, than the population of singles. In such a case, we would expect to find more CTTS ("young and active") than in the singles sample and, consequently, more CC binaries. In Simon & Prato's (1995) results, the median age of their single stars sample is $\log t_{\rm SW} \sim 5.8$. In our sample, we find that half of the primaries have an age assigned by Simon & Prato older than this value. We thus conclude that our study includes about as many young systems as old systems, and time evolution effects do not impinge our conclusion.

4.2.4. Close companions and hierarchical systems

The issue of how to treat known binaries which we do not resolve is not straightforward. Moreover, currently undetected companions may exist around some of the stars in our sample. These unresolved companions may strongly impact on the evolution and the accretion history of their associated star.
Furthermore, considering a triple system as two independent binaries may not be a valid hypothesis.

To evaluate the impact of such multiple systems, we considered a subsample of binaries where no third component, either spectroscopic (Mathieu 1994), very tight visual (Simon et al. 1995) or wider, is known so far. To our knowledge, only 7 binaries in our overall sample match this criterion: LkCa 7, FX Tau, DK Tau, HK Tau, IT Tau, HN Tau and UY Aur. This subsample contains 6 twins and 1 mixed binaries. Once again, only about $15\,\%$ of these binaries are mixed, leading us to think that the possible existence of additional companions does not significantly modify the results.

4.3. Complementary results from the literature

We have considered previous results in the literature providing information on the classification of the components of more PMS binaries in the Taurus SFR. We complement our results with those of H94 and PS97 and obtain a more than 90 % complete sample of binaries in the separation range $0\farcs8$ to $13''$. The list of these supplementary objects is given in table 3.

To classify the members of binaries studied by H94, we used their Hα EWs and spectral types together with the estimated near-infrared excesses. Both indicators agree well for all stars except for V710 Tau S. This star presents an Hα EW hardly above the classical limit (11 Å), with a spectral type M3, and no infrared excess. Moreover, Cohen & Kuhi (1979), measured an Hα EW of 3.3 Å and no emission in the forbidden lines, leading us to classify this star as a WTTS. V710 Tau consequently happens to be one of the few mixed pairs (CW) among TTS binaries.

For the two binaries studied by PS97 and included in our sample, all stars have $K-L \geq 1.2$ mag. Such high values are strong evidences for the presence of an optically thick accretion

Table 3. Binaries observed by H94 and PS97, listed with the primary first. See text for details on the classification of individual stars

HBC	Object	$\rho('')$	type	ref
352–353	NTTS 035120+3154 SW–NE	8.7	WW	H94
355–354	NTTS 035135+2528 SE–NW	6.3	WW	H94
360–361	NTTS 040142+2150 SW–NE	7.2	WW	H94
386–387	FV Tau–FV Tau/c	12.3	CC	H94
389	Haro 6-10	1.2	CC	PS97
51–395	V710 Tau N–S	3.2	CW	H94
52–53	UZ Tau E–W	3.8	CC	H94
54	GG Tau–GG,Tau/c	10.3	CC	H94
56–57	GI–GK Tau	12.2	CC	H94
411	CoKu Tau/3	2.0	CC	PS97

disk in the inner 0.5 AU around each star (the upper limit for photospheric colors is $K-L \approx 0.4$ mag, Edwards et al. 1993), so that these stars can be safely classified as CTTS. It is also worth mentionning that for all systems common to the PS97's sample and ours (DK Tau and UY Aur with KL photometry and Haro 6-37 with Brγ spectroscopy), their classification and ours are consistent.

When we take these complementary results into account, we obtain 26 binaries with 15 CC twins, 7 WW twins, and 4 mixed. The proportion of mixed systems is then $\approx 15\%$, and even only $\approx 4\,\%$ if we adopt the Hα EW criterion, yielding similar figures as in Section 4.1.

5. Differential accretion in CC binaries

In the binaries of our sample where both stars have active accretion disks (CC pairs), we have used the available spectra to compare the accretion of each component, using their Hα flux as an accretion diagnosis. The Hα EW has already been shown to correlate well with the infrared excess in CTTS (eg. Edwards et al., 1993). Moreover, recent studies in the near infrared where the extinction is about ten times smaller than at Hα wavelengths, have revealed tight correlations between the accretion luminosity and the Paβ and Brγ emission fluxes (Muzerolle et al., 1998). We will then hereafter use the relative Hα flux in binaries, assuming that the Hα flux is proportional to the energy dissipated in the accretion process, i.e., to the accretion luminosity.

We assume that the extinction toward both components of the binary is the same, based on the tight correlation observed in the data of H94 between A_J toward the primary and the secondary. We checked that this correlation is still valid at smaller separations: we evaluated a rough $V\,R$ photometry from our spectra and compared the results to dwarfs colors. Due to observational uncertainties ($\sigma_V \approx \sigma_R \approx 0.1$ mag and 1 subclass for the spectral type), the final accuracy of the extinction is rather poor (typically, $\sigma(A_V) \approx 0.7$ mag). However, we did not find any evidence that the correlation is modified. This correlation is likely due to the fact that both components of a binary system are equally embedded in the Taurus molecular cloud, but other explanations include the existence of a common circumbinary envelope and/or of circumstellar disks with similar orientations. Brandner & Zinnecker (1997) reported a similar correlation for close (< 250 AU) PMS binaries in southern SFRs.

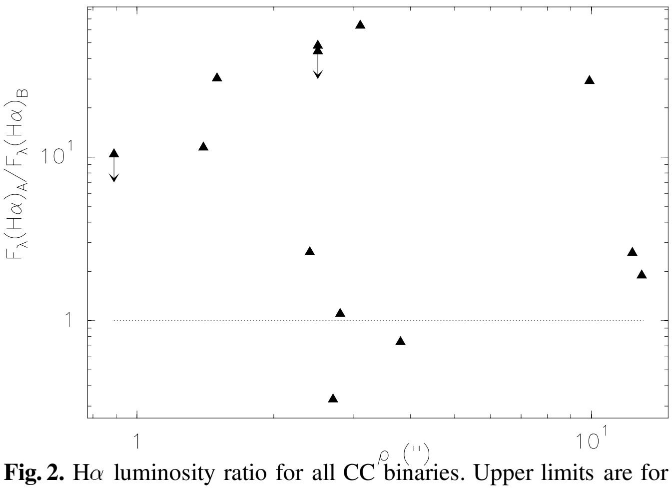

Fig. 2. Hα luminosity ratio for all CC binaries. Upper limits are for UY Aur and HK Tau.

For each binary, the ratio of the Hα luminosities is computed as:

$$\frac{F^A_{H_\alpha}}{F^B_{H_\alpha}} = \frac{\mathrm{EW}^{\mathrm{A}}_\lambda}{\mathrm{EW}^{\mathrm{B}}_\lambda} \times \frac{F^A_c}{F^B_c} 10^{0.4(A^A_V - A^B_V)} \approx \frac{\mathrm{EW}^{\mathrm{A}}_\lambda}{\mathrm{EW}^{\mathrm{B}}_\lambda} \times \frac{F^A_c}{F^B_c}$$

where F_c is the nearby continuum estimated from our spectra when available and from H94's R photometry otherwise.

Figure 2 shows a clear trend for the primaries to have a higher Hα flux than the secondaries, i.e., a higher accretion luminosity. It is unlikely that this result is the consequence of a systematic bias introduced by the assumption that both extinctions are the same. This would imply that the secondaries are, on average, more extincted than the primaries, by about $A^B_V - A^A_V \sim$1.5 mag, which would mean that we systematically overestimated the Hα luminosity ratios by a factor of 4. Such a systematic trend would have been detected in H94 (the authors quote $\sigma(\Delta A_V) \approx 0.3$ mag), as well as in our data. This suggests that the accretion rate is larger on the more massive component of the system.

In a few cases, clues exist that the photosphere is not seen directly, and we only detect scattered light. This is the case for UY Aur B (Close et al. 1998) and HK Tau B (Stapelfeldt et al. 1998) where an edge-on disk has been recently detected. For these stars, the observed photometry is therefore only a lower limit to their actual flux, and we underestimated their Hα flux. Arrows have been accordingly added in Fig. 2. We assume that none of the other stars is heavily scattered.

6. Summary

We have shown that there exists only few mixed systems in Taurus PMS binaries in the separation range 130 - 1800 AU. This result extends those of PS97 who did not find any mixed system in sa sample including binaries with separations of 40–360 AU. This indicates that the accretion history of the two stars are not independent, even for wider binaries, with separations up to 800 AU (from our new spectroscopic observations) and even 1800 AU if we take into account the results of H94.

What could explain such a correlation in binaries with separations as large as 1800 AU ? This "twining" trend, together with the fact that circumstellar disk dissipation times from optically thick to optically thin are short (Simon & Prato 1995), led PS97 to propose that both components of a close binary system accrete over the same time span because their circumstellar disks are replenished by material from a common (circumbinary) environment. As soon as this environment is cleared, both disks dissapear over a short viscous timescale. However, the circumbinary environment hypothesis appears difficult to apply to wide binaries, and if such envelopes have been detected around a few close binaries they remain elusive. Similarly, it appears unlikely that the binary as a whole can sweep enough material during its wander through the parent cloud: at 1 km.s^{-1}, a 100 AU radius wide binary sweeps only $10^{-12}\,M_\odot.yr^{-1}$ in a 10^2 cm^{-3} density cloud.

On the other hand, we find that the primaries have larger Hα fluxes than their secondaries. We call 'primary' the brightest component in the V band, which always has an earlier spectral type than the secondary so that it is likely the most massive star. The Hα luminosity is assumed to be proportional to the accretion luminosity:

$$L_{\mathrm{H}\alpha} \propto L_{\mathrm{acc}} = \frac{GM_\star \dot{M}}{R_\star}$$

Baraffe et al. (1998)'s evolutionary models, show that two 2 Myr-old TTS with masses of 1 $M_\odot$ and 0.1 $M_\odot$ have $M_\star/R_\star$ ratios only differing by a factor of 4 (the most massive star also has a larger radius). Our measured Hα luminosity ratios vary by over 2 orders of magnitude, and therefore cannot be accounted for by extreme mass ratios. The difference in the accretion luminosities is thus likely to reveal that, in most cases, the primary accretes more than its companion: $\dot{M}_A > \dot{M}_B$. It is also noticeable that the mixed systems in our sample all have a CTTS primary, so that in the case of CW pairs, the more massive star again seems to be more active than the other one.

In order to have similar disks lifetimes $\tau = M/\dot{M}$, this suggests that during the early binary formation process, the circumprimary disk is preferentially feeded by the common parental reservoir of mass, a result in agreement with the prediction of Bonnell et al. (1992) model.

Another possibility could be that the accretion rate on the star $\dot{M}$ is proportional to the disk mass, itself related to the central star' mass. In the canonical accretion disk theory, the accretion rate $\dot{M}$ is related to the surface density Σ, itself evidently linked to the disk mass. This would explain simultaneously why $\dot{M}_A > \dot{M}_B$ and why the disk lifetime $\tau = M/\dot{M}$ is the same, independently of the mass of the central star, as shown by the small amount of mixed systems observed. If true, such a $M - \dot{M}$ relation should hold for single TTS but current mass and accretion rates determination lack the precision needed to study this point further.

Observations of closer PMS binaries down to separations of the order of the peak value in their separation distribution (≈ 50 AU, Mathieu 1994) should shed more light on the study of their relative accretion. Such observations are within reach of current adaptive optics systems equiped with spectroscopic capabilities. Such a peak separation is of the order of the size of a canonical accretion disk and these observations would allow to study systems where the star-disk and disk-disk interactions are strong, and also where the eventual leftover circumbinary environment has a major influence.

Acknowledgements. We are grateful to Caroline Terquem and Mike Simon for enriching discussions. Comments from an anonymous referee significantly improved this paper. This research has made use of the Simbad database, operated at CDS, Strasbourg, France, and of the NASA's Astrophysics Data System Abstract Service.

Table A1. Additionnal emission line measurements from our spectra. All equivalent widths are given in A. Stars that are not listed here were not detected in any of these lines.

HBC	object	Hγ	Hδ	[O I] λ6363	[S II] $\lambda\lambda$6716,31
358	HBC 358 A	9.5	5.1	–	–
	HBC 358 B	4.8	11.5	–	–
	GG Tau/c A	12	–	–	–
57	GK Tau A	10.2	7.0	–	–
	IT Tau A	3.4	–	–	–
	IT Tau B	35±5	–	–	–
76	UY Aur A	24	8.0±1.0	–	–
	UY Aur B	13	–	2.1	1.2
80	RW Aur A	1.1	3.1	–	–
	RW Aur B	–	–	0.8	–

Appendix A: Complementary line measurements

In our new spectroscopic observations, some stars were detected in emission in other lines than is presented in Table 2. EW measurements for Hγ, Hδ, [O I]$\lambda 6363$ and the doublet [S II]$\lambda\lambda 6716, 31$ lines are given in Table A1 for the stars where these lines were detected.

References

Allen L., Strom K., 1995, AJ, 109, 1379
Armitage P., Clarke C., Tout C., 1999, MNRAS, in press
Artymowicz P., Lubow S., 1996, ApJ, 476, L77
Baraffe I., Chabrier G., Allard F., Hauschildt P., 1998, A&A, 337, 403
Basri G., Batalha C., 1990, ApJ, 363, 654
Bastian U., Finkenzeller U., Jaschek C., Jaschek M., 1983, A&A, 126, 438
Bate, M.R., Bonnell, I. A., 1997, MNRAS, 285, 33
Bertout, C., 1989, ARA&A, 27, 351
Bonnell I., Bastien P., 1992, ApJ, 401, 654
Bonnell I., Arcoragi J.-P., Martel H., Bastien P., 1992, ApJ, 400, 579

Boss A., 1993, ApJ, 410, 157
Boss A., 1997, ApJ, 483, 309
Brandner W., Zinnecker H., 1997, A&A, 321, 320
Burkert A., Bate M., Bodenheimer P., 1997, MNRAS, 289, 497
Chen H., Myers P., Ladd E., Wood D., 1995, ApJ, 445, 377
Close L., Dutrey A., Roddier F., Guilloteau, S. Roddier C., Duvert G., Northcott M., Ménard F., Graves J., Potter D., 1998, ApJ, 499, 883
Cohen M., Kuhi L., 1979, ApJS, 41, 743
Duchêne G., 1999, A&A, 341, 547
Duquennoy A., Mayor M., 1991, A&A, 248, 485
Dutrey A., Guilloteau S., Prato L., Simon M., Duvert G., Schuster K., Ménard F., 1998, A&A, 338, L63
Duvert G., Ménard F., Dutrey A., Guilloteau S., Simon M., 1999, A&A, submitted
Edwards S., Ray T., Mundt R., 1993, in *Protostars and Planets III*, eds. E. Levy and J. Lunine, Tucson: the University of Arizona press, p. 567
Favata F., Micela G., Sciortino S., 1997, A&A, 326, 647
Geoffray H., Monin J.-L., 1999, A&A, in preparation
Ghez A., Neugebauer G., Matthews L., 1993, AJ, 106, 2005
Gomez M., Hartmann L., Kenyon S., Hewett R., 1993, AJ, 105, 1927
Hartigan P., Strom K., Strom S., 1994, ApJ, 427, 961 (H94)
Hartmann L., Stauffer J., Kenyon S., Jones B., 1991, AJ, 101, 1050
Herbig G., Bell K., 1988, Lick Observatory Bulletin n$^{\circ}$ 1111 (HBC)
Hirth G., Mundt R., Solf J., 1997, A&AS, 126, 437
Jensen E., Mathieu R., Fuller G., 1996, ApJ, 458, 312
Kenyon S., Hartmann L., 1995, ApJs, 101, 117
Kirkpatrick D., Henry T., McCarthy D., 1991, ApJS, 77, 417
Köhler R., Leinert Ch., 1998, A&A, 331, 977
Larson R., 1995, MNRAS, 272, 213
Leinert C., Weitzel N., Zinnecker H., Christou J., Ridgeway S., Jameson R., Haas M., Lenzen R., 1993, A&A, 278, 129
Lin D., Papaloizou J., 1993, in *Protostars and Planets III*, eds. E. Levy and J. Lunine, Tucson: the University of Arizona press, p. 749
Martín E., 1998, A&A, 115, 351
Martín E., Rebolo R., Magazzú A., Pavlenko Ya., 1994, A&A, 282, 503
Mathieu R., 1994, ARA&A, 32, 465
Moneti A., Zinnecker H., 1991, A&A, 242, 428
Monin J.L., Ménard F., Duchêne G., 1998, A&A, 330, 310 (paper I)
Muzerolle J., Hartmann L., Calvet N., 1998, AJ, 116, 2965
Papaloizou J., Pringle J., 1977, MNRAS, 181, 441
Prato L., Simon M., 1997, ApJ, 474, 455 (PS97)
Reipurth B., Zinnecker H., 1993, A&A, 278, 81
Sigalotti L. Di, Klapp J., 1997, ApJ, 474, 710
Sigalotti L. Di, Klapp J., 1997, A&A, 319, 547
Simon M., Prato L., 1995, ApJ, 450, 824
Simon M., Ghez A., Leinert C., Cassar L., Chen W., Howell R., Jameson R., Matthews K., Neugebauer G., Richichi A., 1995, ApJ, 443, 625
Skrutskie M., Dutkevich D., Strom S., Edwards S., Strom K., 1990, AJ, 99, 1187
Stapelfeldt K.R., Krist J.E., Ménard F., Bouvier J., Padgett D.L., Burrows C.J., 1998, ApJ, 502, L65
Strom K., Strom S., Edwards S., Cabrit S., Skrutskie M., 1989, AJ, 97, 1451
Walter F., Brown A., Mathieu R., Myers P., Vrba F., 1988, AJ, 96, 297
Wichmann R., Krautter J., Schmitt J., Neuhäuser R., Alcalá J., Zinnecker H., Wagner R., Mundt R., Sterzik M., 1996, A&A, 312, 439
White R., Ghez A., Reid I., Schultz G., 1999, ApJ, in prep.