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A 1.3 mm dust continuum survey of Hα selected T Tauri stars in Lupus*

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Abstract. We have observed a sample of 32 Hα selected T Tauri stars in the Lupus 2 and 3 T association with the facility bolometer at the SEST and detected cold dust emission at 1.3 mm from 12 of the objects. For the remaining objects we have derived 3σ upper limits ($\approx$ 40 mJy), which suggest that the cold dust masses are less than $5 \cdot 10^{-5}$ M$_{\odot}$. For stellar masses below 0.7 M$_{\odot}$ the mean disk mass (gas + dust) is approximately 3 % of the stellar mass.

The face value detection rate (38 %) of the Lupus stars is very similar to that of young stars in the Taurus-Auriga association. Thus, the young stellar population in Lupus seems to have an equal incidence of circumstellar disks. In comparison to Taurus-Auriga the low-mass pre-main sequence stars in Lupus show a lack of disk masses below $3 \cdot 10^{-3}$ M$_{\odot}$ (gas + dust), which in part can be explained by the absence of weak-line T Tauri stars in our sample.

Both samples show a strong correlation between relative disk mass and stellar age. Considering the absolute disk mass of 1.3 mm detected sources in Lupus we see a tentative decrease with increasing age, too, while there is no correlation for the Taurus-Auriga sample. This effect might be due to different modes of star formation: isolated star formation in Taurus-Auriga versus clustered star formation in Lupus. Considering both samples globally none of the 6 stars older than 3 Myr shows dust emission, which could mean that almost no small dust grains are left over in the disk at this age. Furthermore, for both samples we do not see any indication that more massive stars have more massive disks. On the contrary, statistical tests suggest that the absolute disk mass as well as the relative disk mass decreases with increasing stellar mass.

Finally, in order to investigate the age-dependent behaviour of the spectral energy distribution, we have determined the IR indices $\alpha_{\rm IR}$ between $\lambda = 2.2\,\mu$m and $\lambda = 12\ldots25\,\mu$m (IRAS) for 11 sources of our sample. According to the revised IR classification by André & Montmerle (1994) these objects belong to the IR class II. Neither a correlation between the infrared indices and the stellar age nor between the infrared indices and the disk mass could have been found.

Key words: stars: circumstellar matter – stars: formation – stars: late-type – stars: low-mass – stars: pre-main sequence – radio continuum: stars

1. Introduction

The evolutionary classification scheme of Young Stellar Objects (YSOs) originally introduced by Lada (1987) and revised by André & Montmerle (1994) predicts a progressive decrease of the amount of circumstellar material from IR class 0 to IR class III, i.e. a decrease with stellar age. The classification is based on the infrared excess of the sources, as measured by the spectral index $\alpha_{\rm IR} = {\rm d}\log(\lambda F_{\lambda}) / {\rm d}\log\lambda$ between $\lambda = 2.2$ and $10\ldots25\,\mu$m, which is attributed to the presence of circumstellar dust.

While for embedded sources (IR class 0 / I) most of the circumstellar matter is distributed in a extended infalling envelope with a typical size of about 10^4 AU (e.g. Adams et al. 1987, Terebey et al. 1993), for the later stages of T Tauri stars (IR class II / III) the IR emission is arising from circumstellar disks on the order of 100 AU in size (e.g. Adams et al. 1988, Bertout et al. 1988, André & Montmerle 1994).

However, infrared observations give only poor estimates of the amount of circumstellar material around YSOs, because shortward of 100 μm the envelope / disk is generally optically thick. Unlike at mm wavelengths the IR range is also much more sensitive to the temperature and density distribution of the circumstellar material and probes only the warm regions close to the central star.

In contrast, observations of dust continuum emission in the mm range provide an excellent way to track the circumstellar evolution of YSOs. Because dusty envelopes / disks around pre-main sequence (PMS) stars are optically thin at wavelengths of the order of 1 mm, the flux density is proportional to the total

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mass (Beckwith et al. 1986; Sargent & Beckwith 1987). Thus, it is possible to estimate the gas and dust masses around YSOs directly from the measured mm flux densities.

2. Sample of objects

The Lupus dark cloud (for a detailed review see Krautter 1991) is one of the nearest (140 ± 20 pc) sites of low-mass star formation (Hughes et al. 1993). Its mass function is dominated by M-type stars with $M_* \leq 0.5\,M_\odot$. Most of the optically visible young stars in Lupus were identified on the basis of their Hα emission in a deep objective prism survey by Schwartz (1977). Spectroscopic and infrared observations were carried out by Appenzeller et al. (1983) and Krautter & Kelemen (1987). Hughes et al. (1994) estimated the effective temperatures of the stars from their spectral types, calculated the reddening towards each object from the (R−I) colors, and derived mass and age distributions for the Lupus stars based on pre-main sequence evolutionary tracks by D'Antona & Mazzitelli (1994).

It is necessary to stress that our sample of young objects in Lupus is Hα selected, i.e. it contains only optically visible sources: 28 classical T Tauri stars (CTTS) and 4 weak-line T Tauri stars (WTTS). Thus, it is heavily biased towards CTTS and class II sources. Neither class III sources, as those revealed by X-ray surveys (cf. Krautter et al. 1997, Wichmann et al. 1997), nor embedded sources (class 0 / I) are contained. As it is important to investigate the frequency of circumstellar disks and to study their properties in various star forming regions, e.g. to see if it depends on local conditions, we compare in this paper our results in detail with those obtained for young objects in the Taurus-Auriga association by Beckwith et al. (1990) and Osterloh & Beckwith (1995). From their mm surveys we have extracted an adequate subsample of 78 Hα selected T Tauri stars (54 CTTS and 24 WTTS) which is well comparable to our Lupus sample. Furthermore, we refer to results reported by Henning et al. (1993) and André & Montmerle (1994) for YSOs in Chamaeleon and Ophiuchus, respectively.

3. Observations

The observations were performed in July 1993 at the 15 m Swedish ESO Submillimetre Telescope (SEST). We used the single channel facility bolometer with a beamsize of 24″ (HPBW). The quality of the telescope pointing was estimated to be about 3″, while the stellar positions were taken from Schwartz (1977) and are accurate within 1″ to 2″. Chopping was done with the focal plane chopper operating at 4.5 Hz with a beam separation of 70″ in azimuth. We used the standard ON-OFF procedure and performed measurements consisting of 10 cycles with 20 s integration time each. Strong sources were observed at least twice, fainter objects up to four times, resulting in an effective sensitivity of about 13 mJy (1σ). The atmospheric opacity frequently determined by skydips was high but fairly stable with a value of 0.33 at zenith. Uranus was used as a calibration standard adopting a brightness temperature of 97 K at 1.3 mm and an estimated calibration uncertainty of ± 20 %.

4. Results

4.1. Ensemble statistics

Fig. 1a shows the H-R diagram of the 32 Hα selected T Tauri stars in Lupus (Hughes et al. 1994) in comparison to that of 78 young stars in Taurus-Auriga (Fig. 1b; Beckwith et al. 1990; Osterloh & Beckwith 1995). Sz 102 falls below the main sequence due to strong veiling and lies outside the plot range. Hence, no values for stellar mass and age are given for Sz 102. Following Hughes et al. (1994) we have used new PMS evolutionary tracks and isochrones (D'Antona & Mazzitelli 1994), based on Alexander opacities (Alexander et al. 1989) and Canuto & Mazzitelli convection theory (Canuto & Mazzitelli 1990, 1992), in order to derive the mass and age distribution for our sample of stars. The $\log T_{\rm eff}$ and $\log L_*$ values are taken from Hughes et al. (1994), too. As Beckwith et al. (1990) calculated the stellar masses and ages of the Taurus-Auriga stars using convective tracks and isochrones provided by Vandenberg (1983), we recalculated the stellar masses and ages with the D'Antona & Mazzitelli PMS evolutionary tracks and isochrones (Nürnberger 1995) for a better comparison with the mass and age distribution of the Lupus stars.

As shown in the histograms of Figs. 1c and 1d the Lupus sample represents a distribution of slightly less massive stars than the Taurus-Auriga sample: the mean mass is $0.29\,M_\odot$ and $0.58\,M_\odot$, the median mass is $0.29\,M_\odot$ and $0.39\,M_\odot$ for the T Tauri stars in Lupus and Taurus-Auriga, respectively. The limited range of stellar masses in Lupus (≈ 85 % of our sample stars have masses between $0.1\,M_\odot$ and $0.5\,M_\odot$) is obvious. Only Sz 68 has a mass considerably higher than $0.5\,M_\odot$. Note that the stellar masses of 5 T Tauri stars (Sz 70, Sz 81, Sz 84, Sz 100, and Sz 104: $M_* \leq 0.1\,M_\odot$) are lying close to the regime of brown dwarfs ($M_* \leq 0.08\,M_\odot$).

Furthermore, the stars in the Lupus T associations are on average approximately of the same age as those in the Taurus-Auriga star forming region (Figs. 1e and 1f). While for Lupus the mean stellar age is about 0.4 Myr, that of the young stars in Taurus-Auriga is about 0.3 Myr. An upper limit for the Lupus age distribution occurs at log t/yr ≈ 6.7, which deviates from the value of log t/yr ≈ 7.0 found by Hughes et al. (1994), because our Lupus sample constitutes only a subsample. Due to neglect of accretion for the PMS tracks and due to unknown multiplicity for most stars (see Sect. 4.2), ages that young have a relatively large uncertainty. Unknown multiplicity mainly influences the determination of the luminosity of the star and therefore underestimates the stellar age and to a lesser degree the stellar mass, depending on the position in the H-R diagram (Simon et al. 1993, Brandner & Zinnecker 1997).

4.2. Detection rate

The results of our 1.3 mm dust continuum observations in Lupus are shown in Table 1 together with some basic physical parameters taken from Hughes et al. (1994). Column 9 of Table 1 lists the measured 1.3 mm flux density and column 10 the corresponding statistical uncertainty (1σ). Note that detections

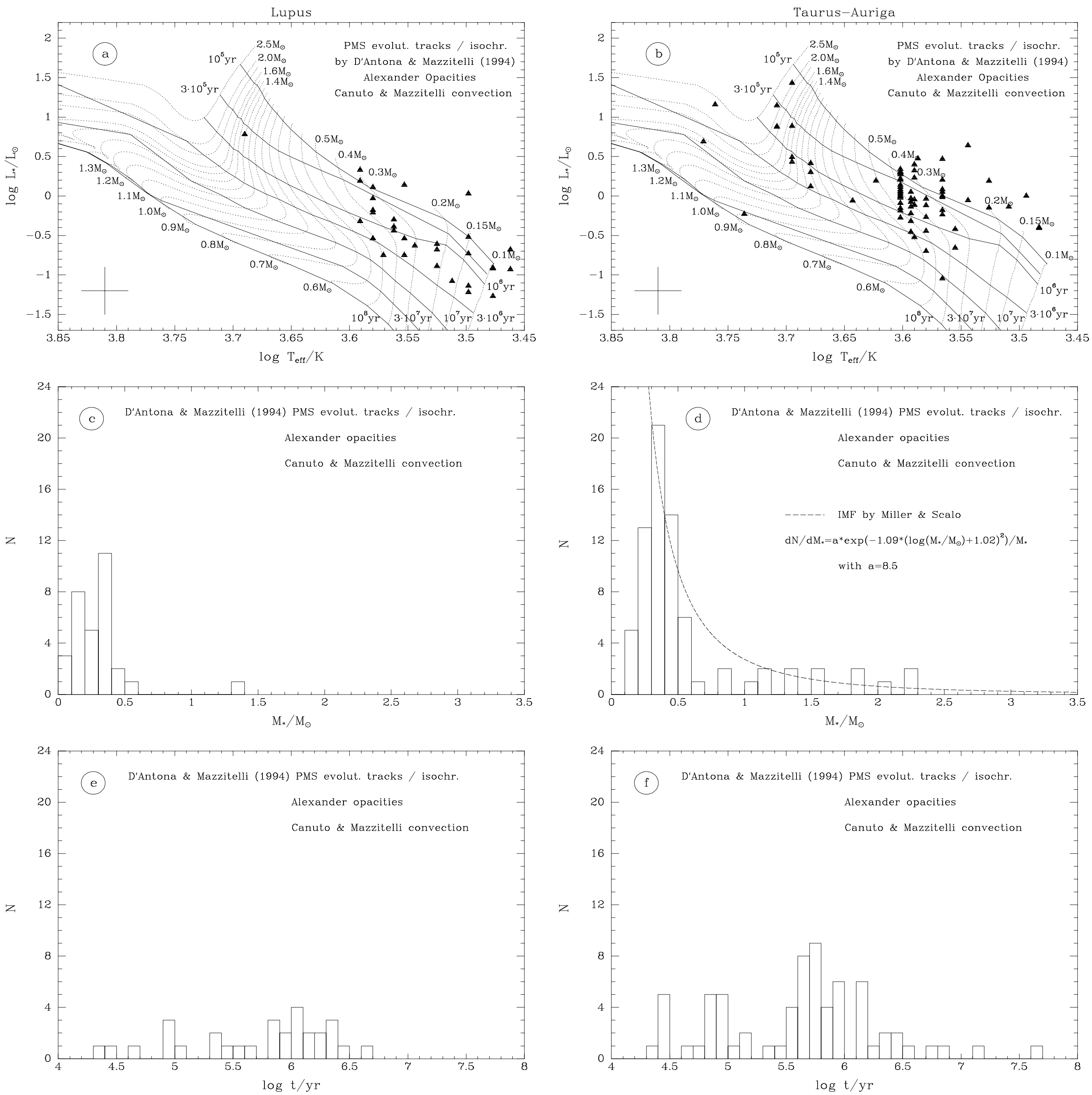

Fig. 1a–f. Graphical summary of pre-existing properties of our sample of 32 Hα selected T Tauri stars in Lupus (left; Hughes et al. 1994) compared with those of a sample of 78 T Tauri stars in Taurus-Auriga (right; Beckwith et al. 1990, Osterloh & Beckwith 1995). From top to bottom are shown the positions of the stars in the H-R diagram (**a**),(**b**) as well as the distributions of stellar masses (**c**),(**d**) and ages (**e**),(**f**). Additionally, for the Taurus-Auriga sample the IMF following Miller & Scalo (1979) is given assuming completeness in the range of stellar masses from 0.3 $M_\odot$ to 2.5 $M_\odot$. A cross in the lower left corner of the H-R diagrams (a, b) gives $\log T_{\rm eff}$ and $\log L_*$ errorbars typical for T Tauri stars with stellar masses of approximately 0.5 $M_\odot$ and ages of about 1 Myr.

Table 1. Measured and derived parameters for 32 Hα selected T Tauri stars in Lupus.

Name	Aliases	Sp.T. [1]	$EW_{H\alpha}$/Å [1]	log $L_*/L_\odot$ [1]	log T_{eff}/K [1]	log t/yr [1]	$M_*/M_\odot$ [1]	$F_{1.3mm}$ (mJy)	σ (mJy)	M_{disk} ($10^{-3}M_\odot$)	M_{disk}/M_* (%)
Sz 65$^+$		M0	19.4	-0.03	3.58	5.6	0.33	**56**	10	**6.4**	**1.9**
Sz 66$^+$		M3	63.7	-0.61	3.52	6.0	0.23	**47**	12	**5.4**	**2.3**
Sz 67		M4	5.9	-0.52	3.50	5.0	0.15	<66	22	<7.4	<4.9
Sz 68$^+$	HRC 248	K2	2.8	0.78	3.69	5.6	1.3	**135**	15	**15.5**	**1.2**
Sz 69	Th 2	M1	306.5	-0.44	3.56	6.0	0.37	<30	10	<3.4	<0.9
Sz 70		M5	19.4	-0.91	3.48	5.3*	0.10*	<45	15	<5.2	<5.2
Sz 71	GW Lup, HRC 249	M2	90.3	-0.63	3.54	6.1	0.30	**106**	18	**12.2**	**4.1**
Sz 72	HM Lup, Th 4	M3	115.3	-0.68	3.52	6.1	0.23	<45	15	<5.3	<2.3
Sz 73	Th 5	M0	97.2	-0.54	3.58	6.4	0.51	**26**	8	**3.0**	**0.6**
Sz 74$^+$	HN Lup, Th 6	M1.5	49.6	0.14	3.55	4.4	0.22	<51	17	<5.7	<2.6
Sz 75	GQ Lup, HRC 250	K7-M0	38.6	0.19	3.59	5.0	0.32	**38**	7	**4.3**	**1.3**
Sz 76		M1	10.3	-0.39	3.56	5.9	0.36	<45	15	<5.0	<1.4
Sz 77$^+$		M0	12.4	-0.18	3.58	5.8	0.38	<45	15	<5.2	<1.4
Sz 81$^+$	Th 10	M5.5	35.8	-0.68	3.46	4.3*	0.08*	**35**	9	**4.0**	**5.0**
Sz 82	Th 12	M0	8.1	0.11	3.58	5.0	0.29	**260**	9	**29.9**	**10.3**
Sz 83	RU Lup, Th 13	K7-M0	216.4	0.33	3.59	4.6	0.30	**197**	7	**22.7**	**7.6**
Sz 84		M5.5	43.7	-0.93	3.46	4.9*	0.07*	<36	12	<4.2	<6.1
Sz 88$^+$	HO Lup, Th 18	M1	219.8	-0.30	3.56	5.8	0.33	<24	8	<2.7	<0.8
Sz 90	Th 21	K7-M0	28.5	-0.32	3.59	6.1	0.49	**26**	9	**3.0**	**0.6**
Sz 91$^+$	Th 20	M0.5	95.9	-0.75	3.57	6.7	0.49	<27	9	<3.2	<0.7
Sz 94		M4	7.3	-1.14	3.50	6.3	0.13	<45	15	<5.0	<3.9
Sz 95		M1.5	10.2	-0.75	3.55	6.4	0.35	<36	12	<4.2	<1.2
Sz 96		M1.5	11.0	-0.54	3.55	6.1	0.34	<45	15	<5.3	<1.6
Sz 97	Th 24	M3	58.2	-0.89	3.52	6.2	0.21	**28**	9	**3.2**	**1.5**
Sz 98	HK Lup	M0	29.1	-0.21	3.58	5.8	0.39	**84**	17	**9.7**	**2.5**
Sz 99	Th 25	M3.5	49.8	-1.08	3.51	6.3	0.16	<30	10	<3.6	<2.2
Sz 100	Th 26	M5	21.4	-0.92	3.48	5.3*	0.10*	<27	9	<3.2	<3.2
Sz 101$^+$	Th 27	M4	26.0	-0.73	3.50	5.5	0.14	<39	13	<4.6	<3.3
Sz 102	Th 28	K0	377.4	-1.94	3.72	-	-	<30	10	<3.3	-
Sz 103	Th 29	M4	33.1	-1.22	3.50	6.3	0.12	<57	19	<6.7	<5.6
Sz 104	Th 30	M5	13.3	-1.27	3.48	6.1*	0.08*	<42	14	<4.8	<6.1
Sz 105$^+$	Th 31	M4	63.9	0.03	3.50	3.7	0.15	<33	11	<3.9	<2.6

Notes: 1.3 mm detections are printed in bold letters, whereas upper limits (3σ) are indicated by a "<". Independent observations by Reipurth et al. (1993) yielded a 1.3 mm flux density of 122 ± 12 mJy for Sz 68 and an upper limit of 34 mJy for Sz 102. Some mass and age values (indicated by *) were recalculated as the values given by [1] differ from the position of the stars in the H-R diagram. For our calculations of the disk masses (gas + dust) from the 1.3 mm flux densities, we adopted a mass averaged dust temperature of 30 K (Nürnberger 1995) and a mass opacity coefficient of 0.02 $cm^2\ g^{-1}$ (Beckwith et al. 1990). A $^+$ behind the source name marks known binaries (Reipurth & Zinnecker 1993, Ghez et al. 1997). The binary system Sz 65/66 (ang. sep. 6.″4) was not resolved by the SEST beam (HPBW 24″), but the different flux values are a result of the telescope pointing on each of the two binary components.
References: [1] Hughes et al. (1994).

are indicated by bold print, while for non-detections only 3σ upper limits are given for the flux density. An object is considered as detected when its observed flux density is at least three times (3σ) above the measured standard deviation.

Out of the sample of 32 young stars in Lupus we have detected cold dust emission from 12 T Tauri stars which means a face value detection rate of 38 % and is comparable to the detection rate of 42 % and 32 % found in Taurus-Auriga by Beckwith et al. (1990) and Osterloh & Beckwith (1995), respectively. Similar detection rates are also reported by Henning et al. (1993) and André & Montmerle (1994) for T Tauri stars in Chamaeleon (44 %) and Ophiuchus (approximately 15 % and 60 % for IR class III and IR class II sources, which corresponds to detection rates of about 30 % and 50 % for WTTS and CTTS, respectively). Owing to a time-variable atmospheric noise, the uncertainty σ was not constant throughout our observations. Therefore, no uniform lower limit to the flux density could be adopted. Sz 73, Sz 90, and Sz 97 are marginally detected, whereas Sz 88 and Sz 91 are non-detections with respect to the 3σ detection limit. If these five stars are discounted due to their relatively low flux densities the detection rate is about 34 %. As the star forming regions in Lupus and Taurus-Auriga are at virtually the same distance of 140 pc and as the overall sensitivity of our Lupus survey (SEST 15 m, low sky noise) was comparable to the Taurus-Auriga surveys (IRAM 30 m, but high sky noise), the young stellar population in Lupus seems to have an equal incidence of circumstellar disks. On average the $3\,\sigma$ detection limit of both the Lupus and Taurus-Auriga survey was approximately 40 mJy.

Furthermore, in our sample ten sources are known as binaries (Reipurth & Zinnecker 1993, Ghez et al. 1997): Sz 65/66 (ang. sep. $6''\!.4$), Sz 68 ($2''\!.6$), Sz 74 ($0''\!.2$), Sz 77 ($1''\!.8$), Sz 81 ($2''\!.0$), Sz 88 ($1''\!.5$), Sz 91 ($8''\!.7$), Sz 101 ($0''\!.8$), and Sz 105 ($10''\!.9$). Thus, the multiplicity frequency is approximately 31 %, which is consistent with the multiplicity frequency of 42 % found by Leinert et al. (1993) for the separation range from $0''\!.13$ to $13''$ based on their systematic Taurus survey covering 104 young stars. In our Lupus sample only three wider pairs (Sz 65/66, Sz 68, and Sz 81) are detected at 1.3 mm. However, even the separation of Sz 65/66 is not wide enough to resolve the 1.3 mm fluxes of the two components with the telescope beam (HPBW $24''$). Sz 91 and Sz 105 might not be gravitationally bound binaries (Brandner, priv. comm.).

Due to the small number of binaries in our sample no correlation between the 1.3 mm fluxes and the binary separation could be found. In recent studies Simon et al. (1995), Zinnecker (1995), and Jensen et al. (1996) have investigated the connection between submm continuum flux and binary separation for samples of PMS binaries in the star forming regions of Ophiuchus, Taurus, and Scorpius. They found that binaries with projected separations in the range of 1 AU to 100 AU have lower submm continuum fluxes than wider binaries or single stars. This suggests that binaries with separations less than 100 AU significantly influence the nature of their associated disks. Furthermore, the approximate value of 100 AU for the critical binary separation indicates that the characteristic size of disks around T Tauri stars is of the same order. A detailed discussion of disk-destruction due to the existence of a close companion is given by Ghez et al. (1994) and Jensen et al. (1996). Therefore, some stars of our Lupus sample, which are not detected at mm wavelengths, might be close binary systems. The knowledge of stellar multiplicity in Lupus is very limited so far (Reipurth & Zinnecker 1993 for the separation range from $1''$ to $12''$), but a detailed study by Ghez et al. (1997) covering the separation range from $0''\!.12$ to $12''$ will be available soon. We also note that several disk dissipation mechanisms may be at work and tidal disruption by a close companion is only one of them. Coagulation into planetesimals might be another one, as will be discussed in Sect. 4.3.

Anyway, the need and importance of high angular resolution observations both at infrared and mm wavelengths for the accurate discussion and understanding of the companion-disk interaction is stressed by the following example. For the binary Sz 68 Ghez et al. (1997) report an additional IR companion with a projected separation of $0''\!.1$ from the optically brighter component (flux ratio of 0.17 in the K filter), while Brandner et al. (1996) do not see any IR companion down to a flux ratio of 0.05 in K. A close companion at a distance of approximately 14 AU to the optically brighter component would prevent the existence of at least the outer part of a circumstellar disk. Thus, due to the strong 1.3 mm flux density of 135 mJy measured for Sz 68 we might conclude that only the optically fainter component is surrounded by a circumstellar dust disk. But as the 1.3 mm dust emission may alternatively originate from a circumbinary disk, mm observations with an angular resolution of the order of $1''$, i.e. sufficiently high enough to separate the two binary components, will be necessary for the confirmation of any model.

4.3. Circumstellar disk masses

Dusty disks around PMS stars are optically thin at the wavelength of 1.3 mm, as already mentioned above. Therefore, assuming a gas to dust mass ratio of 100 : 1, we were able to calculate the circumstellar disk mass directly from the measured flux density $S_{1.3\mathrm{mm}}$:

$$M_{\mathrm{disk}} = M_{\mathrm{gas+dust}} = \frac{S_{1.3\mathrm{mm}} \cdot d^2}{B(T_{\mathrm{dust}}) \cdot \kappa_{1.3\mathrm{mm}}} \quad ,$$

where $d \approx 140$ pc is the distance to the Lupus star forming region and $B(T_{\mathrm{dust}})$ is the Planck function.

We adopted a mass averaged dust temperature of $T_{\mathrm{dust}} = 30$ K, obtained by fitting Planck functions to the SEDs at far infrared and mm wavelengths (Nürnberger 1995). For this we have ignored the IRAS 100 μm fluxes, as due to the large beamsize they are expected to be contaminated either by emission from an extended cold halo (Natta 1993) or from the molecular cloud, which results in an excess emission at 100 μm. Similar average values for the dust temperature have been found by Reipurth et al. (1993; $T_{\mathrm{dust}} = 36$ K) and André & Montmerle (1994; $T_{\mathrm{dust}} = 30$ K). Anyway, as the dependence of the dust emission on the temperature is linear at mm wavelengths (Rayleigh-Jeans approximation), the disk mass depends only weakly on the exact dust temperature.

On the other hand, the influence of the mass opacity coefficient is more severe. At $\lambda = 1.3$ mm it is taken to be $\kappa_{1.3\mathrm{mm}} = 0.02\ \frac{\mathrm{cm}^2}{\mathrm{g}}$ (as suggested for circumstellar disks by Beckwith et al. 1990), but it is uncertain by a factor of about 5 (e.g. André & Montmerle 1994, Ossenkopf & Henning 1994). The dependence on the composition, shape, and size distribution of the dust grains is discussed in detail in recent reviews by Henning et al. (1993, 1995). The most appropriate dust models for circumstellar disks are those given by Krügel et al. (1994), Ossenkopf & Henning (1994), and Pollack et al. (1994), resulting in values for $\kappa_{1.3\mathrm{mm}}$ which are consistent with the assumption of Beckwith et al. (1990). Additionally, using the Beckwith et al. (1990) value for $\kappa_{1.3mm}$ allows an adequate comparison with a number of already published data sets.

While Beckwith et al. (1990) and Osterloh & Beckwith (1995) derived disk masses for the Taurus-Auriga stars from the spectral energy distribution assuming power laws for the radial temperature and density distributions, we calculated the disk masses for Taurus-Auriga stars directly from their measured flux densities as described above. In this way, a comparison between circumstellar disk masses in Lupus and Taurus-Auriga is based on the same procedure.

Column 11 of Table 1 gives for our Lupus sample the disk masses in units of solar mass, while column 12 lists the disk mass in units of the stellar mass. Again, detections are printed in bold letters. An average upper limit of $5 \cdot 10^{-3}\,M_\odot$ (gas + dust) is derived for non-detections. For detections the mean disk mass is approximately 3 % of the stellar mass.

Fig. 2a shows the distribution of the circumstellar disk mass for Lupus stars. In comparison with the corresponding Taurus-Auriga distribution (Fig. 2b) and taking upper limits into account a lack of disk masses lower than $3 \cdot 10^{-3}\,M_\odot$ is obvious. This is interesting since both surveys seem to have an equal incidence of circumstellar disks due to the comparable overall sensitivities and the comparable detection rates. It might be explained in part by the small number of WTTS in the Lupus sample (see also Sect. 4.4 for statistical tests).

In Figs. 3a and 3b the ratio of circumstellar disk mass to stellar mass (i.e. relative disk mass) is plotted as a function of the stellar mass for both Lupus and Taurus-Auriga. For detected sources with stellar masses lower than $0.7\,M_\odot$ (which is only a virtual border) nearly the same mean relative disk mass is obtained for both samples: 3.4 % for Lupus and 4.7 % for Taurus-Auriga. For detected sources in Taurus-Auriga with stellar masses higher than $0.7\,M_\odot$ the mean relative disk mass (1.8 %) is less than half the value found for stellar masses lower than $0.7\,M_\odot$. This means there is at least no indication that among the T Tauri stars more massive stars have more massive disks. On the contrary, taking upper limits for the disk mass into account (see Sect. 4.4) it is more likely that the disk mass is decreasing with increasing stellar mass. This might be explained by a higher accretion rate for more massive stars (e.g. Yorke 1986, Hillenbrand et al. 1992).

Due to the limited range of stellar masses in the Lupus sample it is interesting to investigate the correlation between the circumstellar disk masses and the stellar ages. In Figs. 3c and 3d the relative disk mass is plotted as a function of the stellar age. The detected 1.3 mm sources both in Lupus and Taurus-Auriga show a decrease of circumstellar matter with increasing age, which is consistent with the evolutionary classification scheme of YSOs (already mentioned above) and stressed by correlation probabilities obtained from statistical tests (again, see Sect. 4.4). For detections only, and in the range $4.5 \leq \log t/\mathrm{yr} \leq 5.5$, the highest relative disk mass is about 10 % in Lupus and 20 % in Taurus. In the range $5.5 \leq \log t/\mathrm{yr} \leq 6.5$ the corresponding values are 4 % and 7 %. Considering both samples globally we note that there is no detection for $\log t/\mathrm{yr} > 6.5$, which (despite of the small number of sources) is in agreement with survival times for the inner part of a disk derived from IR observations (e.g. Skrutskie et al. 1990). Although the absolute time at which PMS stars lose their disks is ill-defined and probably depends on initial conditions (cf. Walter et al. 1988, Montmerle & André 1989, André 1995), this suggests that disks around low-mass PMS stars at this age become undetectable at current sensitivities for mm continuum emission, which can be explained if only a slight amount of small particles is left in the disk. The dust grains may have coagulated to much greater bodies (planetesimals) or may have been dispersed or accreted (Strom et al. 1989).

4.4. Statistical tests

In order to quantify our statistical results we have performed nonparametric tests with the publicly available software package ASURV (LaValley et al. 1992) taking upper limits for the disk mass into account. In detail we have tested the following hypotheses:

- in comparison with the corresponding Taurus-Auriga distribution our sample of sources in Lupus shows a lack of disk masses below $5 \cdot 10^{-3}\,M_\odot$,
- there is a correlation between M_{disk}/M_* and M_* as well as between M_{disk} and M_*, i.e. circumstellar (relative) disk mass decreases with increasing stellar mass,
- there is a correlation between M_{disk}/M_* and t_* as well as between M_{disk} and t_*, i.e. circumstellar (relative) disk mass decreases with increasing stellar age.

By using the Kaplan-Meier Estimator available under ASURV we have tested the first hypothesis and found our assumption confirmed that the Lupus sample lacks disk masses lower than $5 \cdot 10^{-3}\,M_\odot$. The corresponding distributions of disk masses derived from the Kaplan-Meier Estimator are shown in Figs. 2a and 2b. The correlation probabilities returned by various two-sample tests (e.g. Gehan's, Peto & Peto, and Peto & Prentice Generalized Wilcoxon tests) are rather low with an average value of about 30 %. A possible explanation might be given by the small number of WTTS (only 4) in our Lupus sample, while the Taurus-Auriga sample contains 24 WTTS. Anyway, this effect can only be proved by considering a sufficiently large number of X-ray selected WTTS in both samples. Thus, an extensive 1.3 mm study of WTTS in the Lupus star forming regions is highly desirable, but unfortunately has not been performed so far.

Table 2 shows the correlation probabilities obtained for the second and third hypothesis by three statistical test models: the Cox Proportional Hazard model, the Generalized Kendall's Tau model, and the Spearman's Rho model. For both the sample in Lupus and Taurus-Auriga there is probably a weak correlation between decreasing relative disk mass and increasing stellar mass. This result remains the same if considering the disk mass itself as a function of the stellar mass. Furthermore, we see a strong correlation between relative disk mass and stellar age for both the sources in Lupus and Taurus-Auriga, i.e. the relative disk mass decreases with increasing stellar age for both samples. In contrast, considering the absolute disk mass instead of

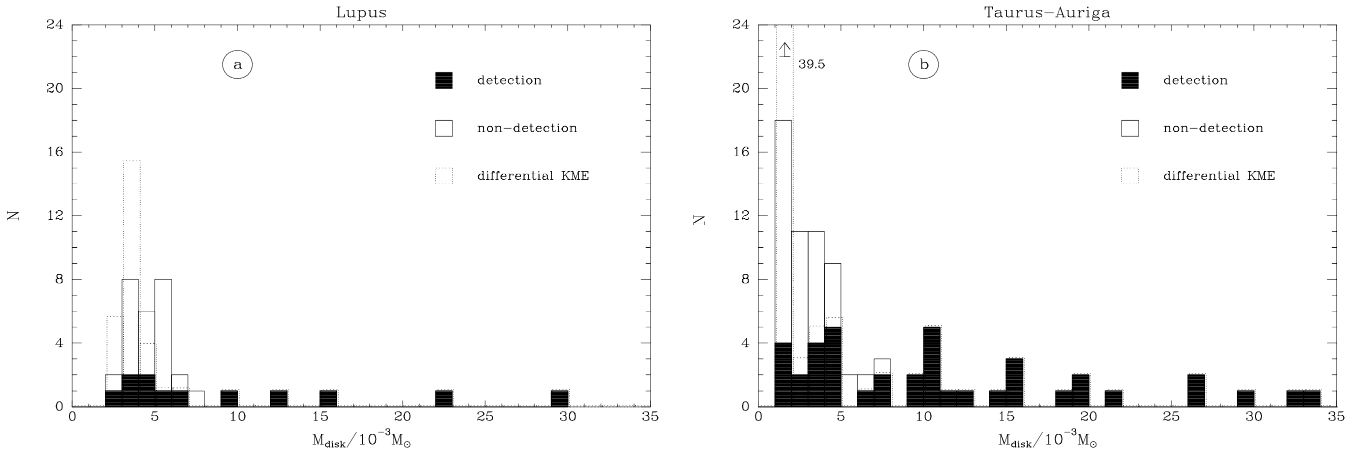

Fig. 2a and b. Distribution of disk masses for our sample of 32 Hα selected T Tauri stars in Lupus (**a**) and the sample of 78 T Tauri stars in Taurus-Auriga (**b**). The slightly offsetted dotted bars give the corresponding distribution of disk masses derived from the the Kaplan-Meier Estimator (KME) taking upper limits for the disk masses into account. In comparison with Taurus-Auriga the lack of disk masses lower than $3 \cdot 10^{-3}$ $M_{\odot}$ is obvious for Lupus. In order to base this comparison on the same procedure we have calculated the circumstellar disk masses for the stars in Taurus-Auriga directly from the measured 1.3 mm flux densities, too, while Beckwith et al. (1990) and Osterloh & Beckwith (1995) derived disk masses from the spectral energy distribution of the sources.

Table 2. Correlation probabilities derived from ASURV test models taking upper limits for M_{disk} into account.

Correlation test model	Correlation between M_{disk}/M_* and M_*		Correlation between M_{disk}/M_* and t_*	
	Lupus	Taurus-Auriga	Lupus	Taurus-Auriga
Cox Proportional Hazard	0.26	0.27	0.99	0.99
Generalized Kendall's Tau	0.80	0.69	0.98	0.98
Spearman's Rho	0.64	0.79	0.97	0.99
	Correlation between M_{disk} and M_*		Correlation between M_{disk} and t_*	
	Lupus	Taurus-Auriga	Lupus	Taurus-Auriga
Cox Proportional Hazard	0.94	0.73	0.74	0.59
Generalized Kendall's Tau	0.74	0.91	0.85	0.39
Spearman's Rho	0.50	0.85	0.90	0.44

Notes: When expressed in terms of an equivalent Gaussian probability, a correlation probability of about 95 % derived from the test models corresponds to a 2σ result.

the relative disk mass we get only a weak correlation with the stellar age for the Lupus sample, while there is obviously no correlation for the Taurus-Auriga sample. Beckwith et al. (1990) and Osterloh & Beckwith (1995) arrived at the same conclusion for the Taurus-Auriga stars.

In order to investigate whether this effect is caused by the large number of WTTS, additionally the same nonparametric tests were applied only to the CTTS contained in the Taurus-Auriga samples. Surprisingly, we find that the correlation probabilities are even slightly lower than those obtained for the whole Taurus-Auriga sample. In other words, the CTTS subsample in Taurus-Auriga shows no correlation between disk mass and stellar age in complete contrast to the behaviour of the CTTS in Lupus. As the stellar properties are approximately the same for T Tauri stars in Lupus and Taurus-Auriga the question arises what is the reason for this difference between the two samples? Is it a result of the star formation process itself?

In fact, the Hα selected T Tauri stars of our Taurus-Auriga sample are associated with small, isolated cores spread over a wide region of the filamentary shaped molecular cloud complex, while the Hα selected T Tauri stars of our Lupus sample are strongly associated with large, massive, and dense molecular cloud cores. Thus, our observations may have revealed a consequence of different modes of star formation: clustered star formation in Lupus versus isolated star formation in Taurus-Auriga (cf. review by Lada et al. 1993 and references therein). While for young stars formed in isolation from each other the properties of the circumstellar environment might be more severely dependent on the initial conditions (e.g. core mass) of the individual star forming process than on the stellar age, for young stars formed in a cluster approximately simultaneously under nearly the same local conditions one would expect that the appearance of the circumstellar material is also dependent on the stellar age.

4.5. Infrared indices

For 11 stars in Table 1 we could calculate infrared indices (columns 7 and 8 of Table 3). Due to a lack of measurements at a wavelength of 10 μm, we have used 12 μm and 25 μm data from

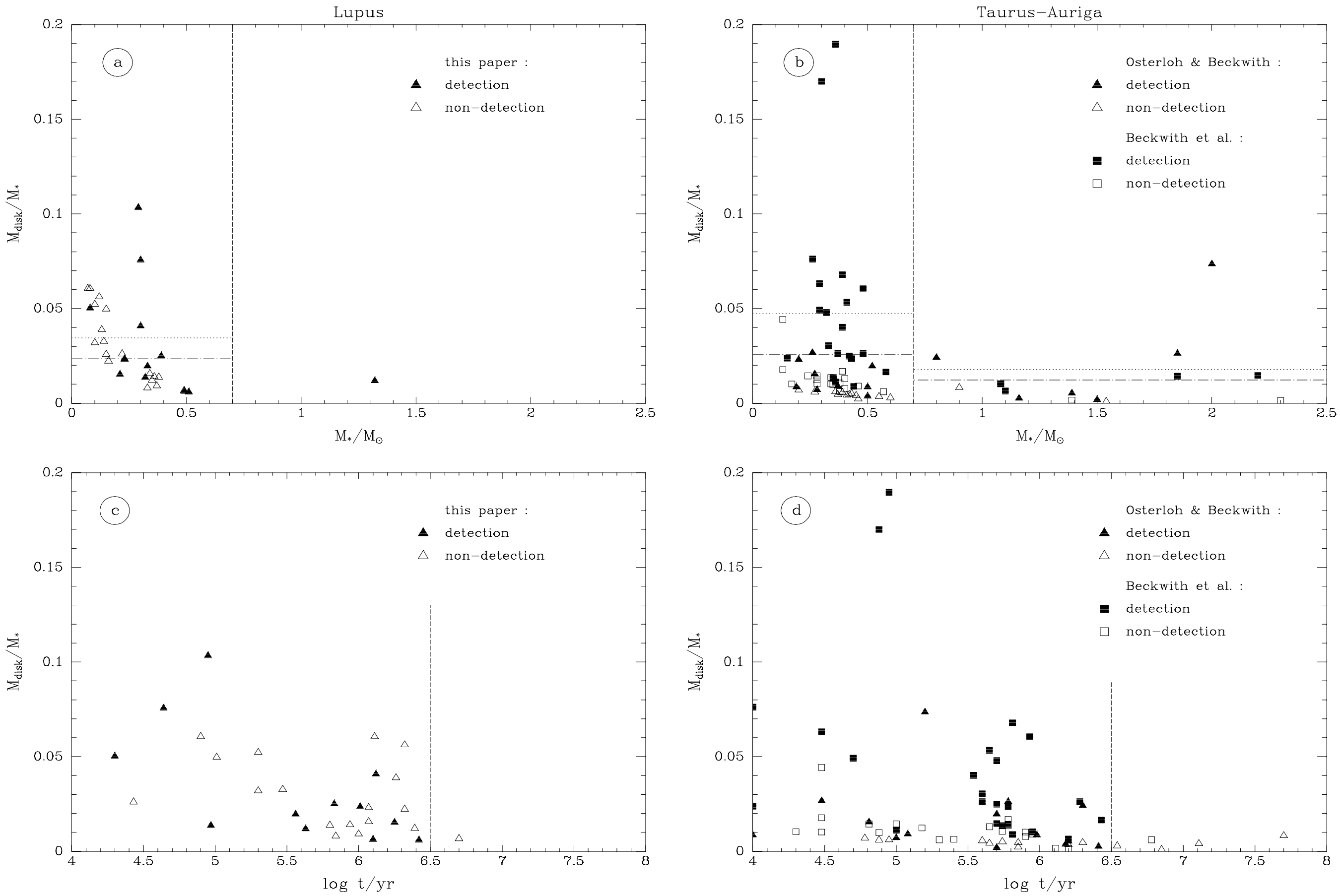

Fig. 3a–d. Ratio of disk mass to stellar mass (relative disk mass) as a function of stellar mass (**a**),(**b**) and age (**c**),(**d**) for our sample of 32 Hα selected T Tauri stars in Lupus (left) and the sample of 78 T Tauri stars in Taurus-Auriga (right). Filled symbols indicate detections on the basis of the 3σ limit. Open symbols mark 3σ upper limits for non-detections. In the figures a and b the dashed line at $M_* = 0.7\,M_\odot$ represents a virtual border between T Tauri stars of 'higher mass' and 'lower mass'. The dotted lines indicate the corresponding mean values and the dash-dotted lines represent the median values, both calculated for 1.3 mm detected objects only. Combining both the Lupus sample and the Taurus-Auriga sample there seems to be no significant indication that more massive stars have more massive disks. Furthermore, considering the star forming regions in Lupus and Taurus-Auriga globally we note that there is no detection for stars older than 3 Myr, which is stressed by a dashed line at log t/yr = 6.5 in the Figs. c and d.

the IRAS Point Source Catalog (columns 5 and 6). All 11 stars belong to the IR class II. While 8 of these are 1.3 mm detections (names are printed in bold letters), 3 count as non-detections. For the remaining 21 objects no corresponding IRAS data exist.

However, we have learned from the star forming region in Ophiuchus (André & Montmerle 1994) that

– weak-line T Tauri stars (WTTS, $EW_{H\alpha} < 10$ Å) represent both class II and class III objects
– nearly all classical T Tauri stars (CTTS, $EW_{H\alpha} > 10$ Å) are class II sources.

In our Lupus sample only 4 stars show an equivalent width of the Hα emission line less than 10 Å (WTTS). Two of them, Sz 68 and Sz 82, are identified as class II sources. Thus, only two WTTS, Sz 67 and Sz 94, remain unclassified in terms of IR class (probably they are class III sources). Both are non-detections at 1.3 mm. Therefore, 19 of 21 stars without IR counterpart can be treated as class II objects because they are CTTS ($EW_{H\alpha} > 10$ Å). In total, if we assume that 30 stars of our sample are class II- and 2 are class III-members, we derive a detection rate of 40 % and 0 % for class II- and class III-stars, respectively. In other words, all of our 1.3 mm detected sources belong to the IR class II.

In Fig. 4a the IR indices are plotted against the stellar age. They show a fairly time-constant behaviour within the range of class II objects. As already mentioned above, the IR index is a tracer for the warm material in the inner part of the disk and reflects the temperature distribution therein, which is a priori unrelated to the total disk mass. This suggests that the small dust particles in regions close to the central star still exist and may not yet have coagulated, dispersed, or accreted in contrast to those in the outer part of the disk.

Fig. 4b illustrates the correlation between the IR indices and the disk masses, derived from the 1.3 mm measurements. No significant correlation is discernable for the class II objects. This is

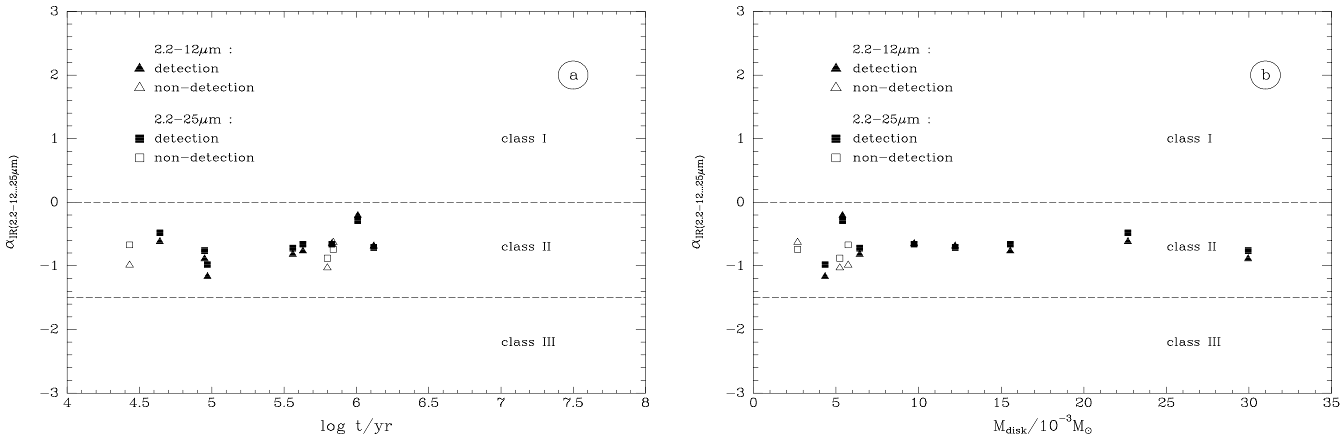

Fig. 4a and b. Infrared indices $\alpha_{IR(2.2-12\mu m)}$ (triangles) and $\alpha_{IR(2.2-25\mu m)}$ (squares) as a function of stellar age (**a**) and disk mass (**b**) for 11 stars in Lupus. Filled symbols indicate detections, open symbols mark non-detections. Neither a correlation between IR index and stellar age nor a correlation between IR index and disk mass could be found.

Table 3. Flux densities and IR classification.

Name	$A_V^{[1]}$	K[1]	$F_{2.2\mu m}$(Jy)	$F_{12\mu m}$(Jy)[2]	$F_{25\mu m}$(Jy)[2]	$\alpha_{IR(2.2-12\mu m)}$	$\alpha_{IR(2.2-25\mu m)}$	IR class
Sz 65+	0.20	7.99	0.41	0.56 ± 0.05	0.82 ± 0.07	-0.82	-0.72	II
Sz 66+	1.05	9.20	0.16	0.56 ± 0.05	0.82 ± 0.07	-0.21	-0.29	II
Sz 68+	1.45	6.55	1.75	2.59 ± 0.13	3.99 ± 0.24	-0.77	-0.66	II
Sz 71	0.00	8.80	0.19	<0.32	0.38 ± 0.05	-0.69	-0.71	II
Sz 74+	2.30	7.38	0.89	0.91 ± 0.07	1.97 ± 0.16	-0.99	-0.67	II
Sz 75	0.95	6.92	1.18	0.88 ± 0.07	1.23 ± 0.15	-1.17	-0.98	II
Sz 77+	0.79	8.34	0.31	<0.30	0.42 ± 0.06	-1.03	-0.88	II
Sz 82	0.98	7.75	0.55	0.67 ± 0.08	1.00 ± 0.12	-0.89	-0.76	II
Sz 83	1.28	6.86	1.29	2.45 ± 0.37	4.55 ± 0.27	-0.62	-0.48	II
Sz 88+	1.25	8.60	0.26	0.49 ± 0.05	0.48 ± 0.05	-0.63	-0.74	II
Sz 98	0.82	7.99	0.44	0.79 ± 0.09	1.00 ± 0.20	-0.65	-0.66	II

Notes: Names of 1.3 mm detected sources are printed in bold letters. A + behind the source name marks known binaries (Reipurth & Zinnecker 1993, Ghez et al. 1997) which were unresolved by the IRAS beams at 12 μm and 25 μm.
References: [1] Hughes et al. (1994), [2] IRAS Point Source Catalog.

not surprising as even within samples containing class I / II / III sources the correlation is weak (André et al. 1990, André & Montmerle 1994). Only when the three classes are considered globally, does a trend emerge (see Figs. 8 and 9 of André & Montmerle 1994).

5. Conclusions

We have presented the results of 1.3 mm dust emission observations of 32 Hα selected T Tauri stars in the Lupus 2 and 3 T association. Out of this sample we have detected 12 objects and derived 3σ upper limits for the remaining objects. Both the detection limit and the detection rate for the T Tauri stars in Lupus is comparable to that of young stars in the Taurus-Auriga star forming region. Thus, the young stellar population in Lupus seems to have an equal incidence of circumstellar disks. Additionally, we note that the detection rate is also in agreement with that obtained for T Tauri stars in Chamaeleon and Ophiuchus.

Taking upper limits for the disk mass into account and in comparison with the corresponding Taurus-Auriga distribution the circumstellar matter around the low-mass PMS stars in Lupus shows a lack of disk masses below $3 \cdot 10^{-3}$ $M_{\odot}$, which might be explained by the small number of WTTS contained in the Lupus sample. For detections the mean disk mass is approximately 3 % of the stellar mass and the ratio of circumstellar disk mass to stellar mass (i.e. relative disk mass) decreases as a function of the stellar age. Considering the star forming regions in Lupus and Taurus-Auriga globally, T Tauri stars older than 3 Myr were not detected at 1.3 mm; they seem to have almost no small dust grains left over in their disks. In order to strengthen these results and to make the comparison to the Taurus-Auriga star forming region more meaningful, an enlargement of our Hα selected Lupus sample at least by a factor of 2 as well as consideration of X-ray selected WTTS (which might outnumber the CTTS at least by a factor of 2) is necessary.

By using statistical methods we have shown that for the detected 1.3 mm sources both in Lupus and Taurus-Auriga the amount of circumstellar dust (in terms of relative disk mass) decreases with increasing stellar age. Investigating whether the disk mass itself is a function of the stellar age, we have found only a correlation for the Lupus sample, while there is no correlation between disk mass and stellar age for the Taurus-Auriga sample. A possible explanation for this effect is given by different modes of star formation: isolated star formation in Taurus-Auriga versus clustered star formation in Lupus. This result has to be proved for other star forming regions like Chamaeleon and Ophiuchus.

Only binaries with separations wider than 2″ (corresponding to a projected separation of 280 AU at the distance of the Lupus star forming region) were detected at 1.3 mm. As the multiplicity of T Tauri stars in the Lupus star forming region is poorly known this could mean that some stars of our Lupus sample, which are not detected at 1.3 mm, might be subarcsecond binary systems and their circumstellar disks might be destroyed due to the existence of a close (separation less than 140 AU) companion. Thus, high spatial resolution studies at optical and IR wavelengths are highly desirable and hopefully will be available soon.

Finally, in order to study in detail the disk parameters of the young stellar population in Lupus, we are currently comparing the observed SEDs from optical to mm wavelengths with our calculations from numerical models including frequency dependent radiation transfer in the disk and a three-component dust model.

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