High spatial resolution observations of the T Tau system - II. Interferometry in the mid-infrared

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Abstract. Each time the resolution was improved, observations of the young low-mass star T Tau led to new insights. Initially classified as the prototype of low-mass pre-main-sequence stars, measurements with high resolution techniques in the near-infrared revealed the existence of a deeply embedded companion only 0.7 arcsec to the south. Later on, this companion itself has been resolved into two sources with a separation of only about 50 mas. We investigated both the optically bright northern component and the embedded southern binary with the MIDI infrared Interferometric instrument (MIDI). The resulting visibilities of the northern component decrease with wavelength, independent of the baseline’s position angle. This is a clear sign of the large face-on circumstellar disc. With a simultaneous fit of a radiative transfer model to both the interferometric results and the spectral energy distribution, the properties of this disc can be determined without the high degeneracy of fits to the spectral energy distribution alone. Since the visibilities of the southern binary are clearly dominated by the typical sinusoidal binary signal, we could for the first time in the mid-infrared derive separate spectra for both components together with a very precise relative position. This position is in excellent agreement with the orbit found from a fit to the near-infrared adaptive optics measurements. The orbit with its small periastron distance indicates tidally truncated discs, which are consistent with the interferometric measurements. The peculiar properties of the infrared companion can be explained by the model of an intermediate mass star extincted by an almost edge-on disc.

1. Introduction
T Tauri is the best characterised triple system of pre-main sequence stars. It allows to investigate the mass and dynamics of the stellar components as well as the structure of discs in an interacting system. Optical long baseline interferometry in the N-band with MIDI nowadays offers an appropriate tool to study the structure of the dusty circumstellar environment, because the provided resolution fits well with the size of the regions responsible for the 10 $\mu$m emission. New results with respect to the orbits and the stellar masses based on adaptive optics measurements in the near-infrared are discussed in the associated contribution to these proceedings [1].

T Tau has been chosen as prototype for a new class of variable objects [2]. It is characterised as a low-mass pre-main sequence star still surrounded by an accretion disc and thus exhibiting large infrared excess. A number of nebulous patches accompanying the source on scales of arcsec show similar spectral features than Herbig-Haro objects. They clearly trace stellar outflows. Today an east-west and a southeast-northwest oriented outflow as well as many interlocking loops and filaments of H$_2$ are known, e.g. [3].

With the advent of speckle interferometry a companion of T Tau was detected in the near-infrared [4]. T Tau S is located only 0.7″ to the south of T Tau N and has been identified as the
source of one of the outflows. In contrast to T Tau N the deeply embedded companion T Tau S is not detectable in the visual. It is a prototypical infrared companion (IRC). But also T Tau S could be resolved into two components that were separated by only 0.05 mas or a projected distance of 7 AU at that time [5, 6]. Over the last decade the separation between T Tau Sa and T Tau Sb rapidly grew to about 130 mas. This orbital motion in combination with the orbital motion of the binary around T Tau N could be used to derive individual masses for T Tau Sa and T Tau Sb [1, 7]. According to these results T Tau Sa is as massive as T Tau N. However, the luminosity is with several tens that of the sun much higher [8]. A large fraction of the visual and near-infrared light emitted by the photosphere of this young stellar object is reprocessed by an almost edge-on circumstellar disc. Furthermore, a circumbinary structure or a foreground screen obscures both southern components and leads to an additional visual extinction of V ≈ 15 mag as it has been found towards the ‘normal’ active low-mass pre-main-sequence star T Tau Sb of spectral type M1.

While T Tau N has shown neither in the visual nor in the near-infrared significant variations, T Tau S exhibits a variability with a total amplitude of ~ 2 mag in the K-, and ~ 3 mag in the L'-band. In the N-band the flux ratio between the southern and the northern component is ~ 0.4 in the minimum and ~ 2.6 in the maximum [9]. The flux ratio of T Tau Sa with respect to T Tau Sb varies between ~ 0.1 and ~ 3.6 in the K-band [5, 10].

Table 1. MIDI observations of the T Tau system.

| Date of Observation | Universal Time | Object | proj. Baseline | Airmass |
|---------------------|---------------|--------|----------------|---------|
| 31-10-2004          | 06:59 - 07:22 | T Tau N | 42.9           | 49.4    | 1.45   |
| 31-10-2004          | 07:22 - 07:41 | T Tau S | 43.9           | 48.9    | 1.49   |
| 02-11-2004          | 05:10 - 05:36 | T Tau N | 85.0           | 87.9    | 1.42   |
| 02-11-2004          | 05:36 - 06:10 | T Tau S | 87.6           | 85.6    | 1.40   |
| 04-11-2004          | 03:54 - 04:36 | T Tau N | 61.6           | 114.0   | 1.56   |
| 04-11-2004          | 04:36 - 05:04 | T Tau S | 62.3           | 111.4   | 1.47   |
2. MIDI measurements
The measurements were carried out within the scope of ‘Guaranteed Time Observations’ (GTO) in autumn 2004. Three different baseline combinations have been used: UT2-UT3 on October 31, UT2-UT4 on November 2, and UT3-UT4 on November 4. The lengths and the position angles of the projected baselines are listed in Table 1. We obtained separate interferometric and spectrophotometric observations for T Tau N and the T Tau S subsystem. The spectra are shown in Figure 2. The visibilities are plotted in Figures 4 & 6.

![Figure 2. The measured spectra of the northern and the southern component (solid black) together with a combined spectrum of the whole source (grey). The individual fluxes of T Tau Sa and T Tau Sb according to the flux ratio from the visibility fits are also shown (dashed black).](image)

3. Dust Processing around T Tau N
The fact that for T Tau N the silicate band appears in emission allows us to model the profile both of the total and the correlated spectra by a mixture of amorphous and crystalline particles of various sizes (Figure 3). Since the correlated spectra preferentially trace the inner and thus hotter emission regions, a comparison between the total and the correlated spectra can be used to find trends of grain growth and crystallisation with decreasing radial distance to the star. Studies have been conducted for selected Herbig Ae/Be stars [11] and the T Tauri star RY Tau [12]. These sources and even the less luminous T Tauri star TW Hya [13] show clear signatures of evolved dust in the inner parts of their discs.

For analysing the total and the correlated spectra of T Tau N we used a widely accepted $\chi^2$-fitting method [14]. It assumes that the silicate emission feature has its origin in the optically thin surface layer of the circumstellar disc where it results from a linear combination of mass absorption coefficients (emissivity) $\kappa_{ij}$ of different dust species $i$ of different size $j$:

$$F(\nu) = B(\nu,T) \left( C_0 + \sum_{ij} C_{ij} \kappa_{ij}(\nu) \right).$$  \hspace{1cm} (1)

In this equation $C_0$ and $C_{ij}$ are fitting parameters. The latter reflects the mass contribution of each component. The quantity $F(\nu)$ is the spectral flux at frequency $\nu$, $\kappa_{ij}(\nu)$ represents the frequency-dependent mass absorption coefficient for a specific component, and $B_\nu(T)$ is the Planck function corresponding to a blackbody temperature $T$. We used a basic dust set of small (0.1 $\mu$m) and large (1.5 $\mu$m) amorphous grains with olivine and pyroxene stoichiometry as well as the crystalline species forsterite, enstatite, and quartz [15]. Carbon is not considered in the
study presented here, because its emission profile is monotonic in the $10\mu m$ wavelength range [16, 17] and thus contributes to the underlying continuum only.

We find from fitting the emission profile of the total flux, corresponding to an emitting region of about 1-20 AU, that small and large amorphous grains are dominating with an abundance of about 50%, 40%, respectively. The remaining 10% are crystalline grains. On the other hand, the correlated flux spectra show clearly the dominant role of large amorphous (50-80%) and crystalline species (20-50%) in the inner few AU of the disc. Here the abundance of small amorphous grains is insignificant.

4. Fitting the Binary Signal of T Tau S

The measurements of T Tau S result in visibilities that decrease with wavelength, increase with spatial frequency $u = B_{\text{proj}}/\lambda$, respectively (Figure 6). This behaviour is typical for emission from a circumstellar disc, where the size of the emitting region grows with wavelength. In contrast the visibilities for T Tau S show sinusoidal oscillations (Figure 4). These oscillations are the signatures of the binary components T Tau Sa and T Tau Sb and carry information about their flux ratio $f$ as well as their projected separation $s$.

In detail, however, the individual components are not point-like, because otherwise the maxima of the normalised visibility would reach a value of 1. Furthermore, the observed amplitudes of the visibility modulations for T Tau S are varying, which demands that the brightness ratio of T Tau Sa to T Tau Sb cannot be independent of wavelength over the 8-13 $\mu m$ range. Therefore, a generalised formula for the binary visibility was used to analyse the interferometric measurements and to determine $f$ and $s$:

$$V(u) = V_0(u) \cdot \frac{\sqrt{1 + f^2(u) + 2fu(u) \cos[2\pi su(u)]}}{1 + f(u)}.$$  \hspace{1cm} (2)

This formula is valid as long as the individual visibilities of T Tau Sa and T Tau Sb are similar and can be approximated by $V_0(u)$. In Equation (2) the polynomials $V_0(u)$ and $s(u)$ are linear with respect to $u$, while $f(u)$ is a polynomial of second order. The resulting fits to the two baselines showing distinct modulations are displayed in Figure 4.
4.1. Relative Position
From these fits a projected separation of $123 \pm 6$ mas along a position angle of $111.4^\circ$ (62 m baseline) and $103 \pm 1$ mas along a position angle of $85.6^\circ$ (85 m baseline) was determined. The actual relative position of T Tau Sb with respect to T Tau Sa is thus

$$d = 124.3 \pm 7.6 \text{ mas},$$

$$\Theta = 299.7 \pm 5.3^\circ,$$

where $d$ is the separation and $\Theta$ the position angle. The relative position is calculated for 10.5 $\mu$m only, because the errors of the fits dominate over the wavelength dependence of the separation. Compared to the near-infrared measurements with adaptive optics these errors are larger. However, the measured relative position is in very good agreement with the recently published orbits [1, 7]. It has to be noted here, that with the solved 180\degree-ambiguity the differential phase identifies T Tau Sb as the fainter source in the N-band [18].

4.2. Flux Ratio
The derived flux ratio is almost independent of the baseline length and reaches a maximum of about 0.7 at 10 $\mu$m. Towards the long and the short wavelength edge of the N-band it drops to about 0.2. This result is confirmed by fitting the correlated fluxes instead of the visibilities.

Applying the mean of the derived flux ratio to the spectrum of T Tau S one finds for T Tau Sa and T Tau Sb the spectra drawn in Figure 1. Both show a clear silicate absorption, but the optical depth is different. With the assumptions that the flux values at 8 $\mu$m and 13 $\mu$m represent the continuum, that this continuum is linear, and that the minimum of the silicate absorption is reached at 10 $\mu$m, one finds towards T Tau Sa a optical depth of $\tau = 1.7$, while towards T Tau Sb the optical depth is only $\tau = 0.5$. The additional extinction towards the infrared companion is a result of the obscuring edge-on disc.

5. Radiative Transfer Code Models
We used the radiative transfer code MC3D [12, 19, 20] to model simultaneously the spectral energy distribution and the visibilities of a source. This code includes the effects of external heating of a disc and an envelope as well as heating by accretion and uses realistic grain properties.
5.1. The northern component

Our best simultaneous radiative transfer model fit to the SED and the visibilities of T Tau N is plotted in Figures 5 & 6. Within this model the star has a temperature of 5250 K and a luminosity of 7.3 $L_\odot$. It is surrounded by an almost face-on disc ($i \approx 20^\circ$) with an inner radius of 0.1 AU, an outer radius of 80 AU, and a mass of 0.04 $M_\odot$ of gas and dust. The scale height of the disc at 100 AU is 18 AU. An additional contribution comes from an envelope whose density at 0.1 AU is by a factor $10^{-5}$ lower than the density of the disc. This envelope extends to the outer radius of the disc and thus forms some kind of additional disc atmosphere. Furthermore, accretion with a rate of $3 \times 10^{-8} M_\odot \text{yr}^{-1}$ has been included. The visual extinction towards T Tau N is only 1.5 mag.

![Figure 5](image1.png)

**Figure 5.** The modeled spectral energy distribution for inclinations of $10^\circ$, $20^\circ$, and $30^\circ$. Measured photometric data are indicated by black crosses. For references see [18]. Arrows indicate upper limits. The grey dashed line represents the stellar photosphere.

![Figure 6](image2.png)

**Figure 6.** The measured calibrated visibilities together with the visibilities derived from the model for an inclination of $20^\circ$. The triangles and the squares represent the upper and lower limits when the position angle of the model is varied.

The parameters of the model are mostly taken from the literature and thus the picture of T Tau N resulting from various studies is well confirmed by our model. Especially the inclination
angle of the disc is restricted to values less than $30^\circ$. On the other hand, the model indicates the presence of a thin envelope. Although accretion leads to similar effects as an envelope, the known accretion rate of T Tau N alone would not be enough to provide the required flux between 3 and $8\,\mu m$. It has to be mentioned here, that the derived radiative transfer model also reproduces the K-band visibilities measured with the Keck Interferometer [21].

![Figure 7](image)

**Figure 7.** *Left:* The modeled spectral energy distributions for T Tau Sa (left) and T Tau Sb (right). For further description see Figure 5. *Below:* Calculated u-v-planes of T Tau Sa at 8.4 $\mu$m, 10.6 $\mu$m, and 12.6 $\mu$m for a disc inclination of $72^\circ$.

5.2. *The southern binary*

According to our model the infrared companion T Tau Sa exhibits a photosphere of 9000 K and has an estimated luminosity of $40\,L_\odot$. It resides within a compact 5 AU disc. The small size of the circumstellar disc around T Tau Sa is probably a result of gravitational truncation by the close companion T Tau Sb orbiting at only a few tens of AU. Due to a comparatively high mass and an inclination of about $72^\circ$ this disc extincts the light very efficiently. However, a foreground extinction of $A_V = 15$ mag is additionally required to reproduce the measured data. Furthermore, a circumbinary disc is present. For the sake of simplicity this circumbinary disc is modeled by extending the inner circumstellar disc out to 50 AU and removing the disc between 5 AU and 30 AU. According to the model also an envelope is present. The accretion rate is with $1 \cdot 10^{-8} M_\odot yr^{-1}$ less than that of T Tau N.

The companion T Tau Sb has a luminosity of $1.8\,L_\odot$ and a photospheric temperature of 3800 K. Also this star is surrounded by a small disc with a size comparable to that of T Tau Sa. However, it is less massive. The inclination of the disc cannot be well determined, but it has to be much lower than that found for the circumstellar disc around T Tau Sa. Accretion seems to
play an important role. For the spectral energy distribution plotted in Figure 7 one needs an accretion rate of \( 6 \cdot 10^{-8} M_\odot \text{yr}^{-1} \). Also for T Tau Sb a foreground extinction of \( A_V = 15 \text{ mag} \) has been taken into account.

The spectral energy distribution is very sensitive to the inclination of the circumstellar disc around T Tau Sa (Figure 7). The found value of 72° in turn puts hard constraints on the orientation of the disc, because it leads to a very elongated shape of the two-dimensional visibility. Although no final conclusion can be drawn yet, an elongation of the disc in north-south direction seems likely (Figure 8). If so, T Tau Sa may be the launching site of the east-west oriented jet.

![Figure 8. The radiative transfer model showing the inner part of the binary system T Tau S at a wavelength of 10.6 \( \mu \text{m} \). The distance between the stars is 18 AU. The stripe spanning the image horizontally is the faint circumbinary disc.](image)

**Acknowledgments**

The author thanks his collaborators in this project: A. A. Schegerer, Ch. Leinert, P. Ábrahám, Th. Henning, T. M. Herbst, R. Köhler, S. Wolf, and H. Zinnecker. He is grateful for the kind support by ESO during the preparation and execution of the observations (run ID: 074.C-0209). Th. R. cordially thanks “Pütz” for sharing sorrow and happiness. Island!

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