

LETTER TO THE EDITOR

# A companion candidate in the gap of the T Chamaeleontis transitional disk<sup>★</sup>

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## ABSTRACT

**Context.** T Cha is a young star surrounded by a cold disk. The presence of a gap within its disk, inferred from fitting to the spectral energy distribution, has suggested on-going planetary formation.

**Aims.** The aim of this work is to look for very low-mass companions within the disk gap of T Cha.

**Methods.** We observed T Cha in  $L'$  and  $K_s$  with NAOS-CONICA, the adaptive optics system at the VLT, using sparse aperture masking.

**Results.** We detected a source in the  $L'$  data at a separation of  $62 \pm 7$  mas, position angle of  $\sim 78 \pm 1$  degrees, and a contrast of  $\Delta L' = 5.1 \pm 0.2$  mag. The object is not detected in the  $K_s$  band data, which show a  $3\text{-}\sigma$  contrast limit of 5.2 mag at the position of the detected  $L'$  source. For a distance of 108 pc, the detected companion candidate is located at 6.7 AU from the primary, well within the disk gap. If T Cha and the companion candidate are bound, the comparison of the  $L'$  and  $K_s$  photometry with evolutionary tracks shows that the photometry is inconsistent with any unextincted photosphere at the age and distance of T Cha. The detected object shows a very red  $K_s - L'$  color, for which a possible explanation would be a significant amount of dust around it. This would imply that the companion candidate is young, which would strengthen the case for a physical companion, and moreover that the object would be in the substellar regime, according to the  $K_s$  upper limit. Another exciting possibility would be that this companion is a recently formed planet within the disk. Additional observations are mandatory to confirm that the object is bound and to properly characterize it.

**Key words.** planetary systems – stars: individual: T Cha – brown dwarfs – instrumentation: adaptive optics – instrumentation: high angular resolution

## 1. Introduction

In recent years, a large number of disks characterized by a lack of significant mid-infrared (IR) emission and a rise into the far-IR have been detected (e.g. Brown et al. 2007; Merín et al. 2010). These are the so-called “transitional disks”, and they are thought to be in an intermediate evolutionary state between primordial Class II protoplanetary disks and Class III debris disks.

The lack of mid-IR excess in cold disks has been interpreted as a sign of dust clearing, which can result in gaps or holes within the disk. These gaps and holes can be created by several mechanisms, such as a close stellar companion, disk photoevaporation, grain growth or a planet formed within the disk. A planet forming within the disk is expected to generate a gap while the dust and gas is accreted onto its surface, sweeping out the orbital region (e.g. Lubow et al. 1999).

In this work, we present high angular resolution deep IR observations of T Cha, a young star with a cold disk. Its

spectral energy distribution (SED) shows a small IR excess between  $1\text{--}10\ \mu\text{m}$  and a very steep rise between  $10\text{--}30\ \mu\text{m}$ . The SED has only been successfully modeled by including a gap from 0.2 to 15 AU (Brown et al. 2007; Schisano et al. 2009). In fact, an inner dusty disk has recently been detected by Olofsson et al. (2011). Because one of the possibilities is that the gap has been cleared by a very low-mass object, we obtained adaptive optics (AO) sparse aperture masking (SAM) observations of T Cha aimed at detecting faint companions within the disk gap.

## 2. The target: T Cha

T Cha is a high probability member of the young  $\epsilon$  Cha association (Torres et al. 2008). It is a G8-type star with a mass of  $\sim 1.5 M_{\odot}$ , classified as a weak-lined T Tauri star based on the  $H_{\alpha}$  equivalent width from single epoch spectroscopy (Alcala et al. 1993). Subsequent photometric and spectroscopic monitoring has indicated a strong variability of this line, which shows significant changes in its equivalent width, intensity, and profile (Gregorio-Hetem et al. 1992; Alcala et al. 1993; Schisano et al. 2009). If the line is related to accretion episodes, then the

<sup>★</sup> Based on observations obtained at the European Southern Observatory using the Very Large Telescope in Cerro Paranal, Chile, under program 84.C-0755(A).

average accretion rate is  $\dot{M} = 4 \times 10^{-9} M_{\odot}/\text{yr}$  (Schisano et al. 2009).

T Cha shows variable circumstellar extinction with a most frequent value of  $A_V = 1.7$  mag according to Schisano et al. (2009). The authors derive a disk extinction law characterized by  $R_V = 5.5$ , which suggests the presence of large dust grains within the disk.

The age of the source is variously estimated to be between 2–10 Myr according to different methods (Fernández et al. 2008). A complete study of the  $\epsilon$  Cha association by Torres et al. (2008) provides an average age of 6 Myr, while da Silva et al. (2009) estimate a slightly older age (between 5–10 Myr) based on the lithium content of the  $\epsilon$  Cha members. Finally, a dynamical evolution study of the  $\eta$  Cha cluster, which probably belongs to the  $\epsilon$  Cha association, provides an age of 6.7 Myr (Ortega et al. 2009). For the purpose of this paper, we adopt an age of 7 Myr.

The distance to the source, based on the Hipparcos parallax, is  $66 \text{ pc} \pm 15 \text{ pc}$ . A more reliable value of  $100 \text{ pc}$  was obtained using proper-motion studies (Frink et al. 1998; Terranebra et al. 1999). Torres et al. (2008) provided a kinematical distance of  $109 \text{ pc}$  for T Cha, and an average value of  $108 \pm 9 \text{ pc}$  for the whole association. We adopted the latter value for this paper.

Finally, previous works based on radial velocity (RV) and direct imaging and coronagraphic techniques have not reported the presence of any (stellar or very low-mass) companion around T Cha (Schisano et al. 2009; Chauvin et al. 2010; Vicente et al. 2011). The SAM observations allow us to fill the gap between RV and direct imaging observations.

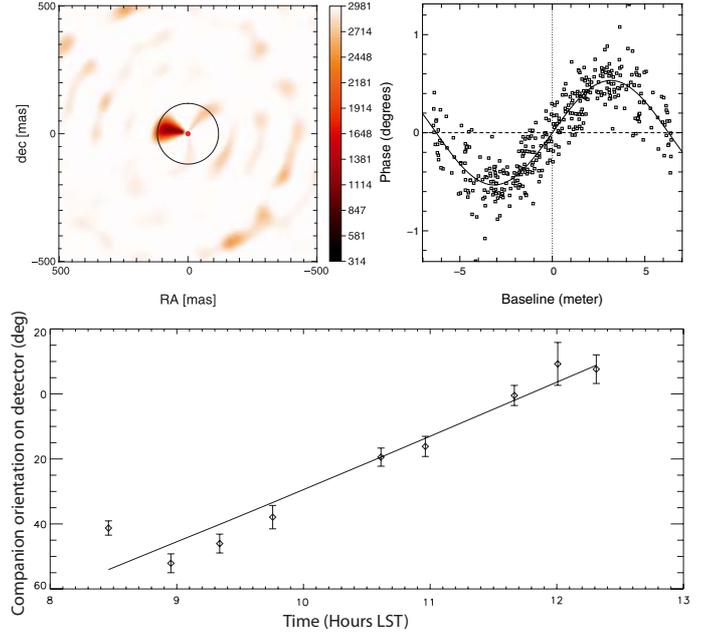
### 3. Observations and data reduction

The observations presented here were obtained with NAOS-CONICA (NACO), the AO system at the Very Large Telescope (VLT), and SAM (Tuthill et al. 2010) in two different campaigns. The  $L'$  observations were obtained in March 2010 under excellent atmospheric conditions (average coherent time of  $\tau_0 = 8 \text{ ms}$ , and average seeing of  $0''.6$ ), while the  $K_s$  data were obtained in July 2010 under moderate atmospheric conditions ( $\tau_0 = 4 \text{ ms}$ , and seeing of  $1''.0$ ).

In March 2010, T Cha was observed with the L27 objective, the seven-hole mask and the  $L'$  filter ( $\lambda_c = 3.80 \mu\text{m}$ ,  $\Delta\lambda = 0.62 \mu\text{m}$ ). The target and a calibrator star (HD 102260) were observed during 10 min each. We repeated the sequence star+calibrator nine times, integrating a total of 48 min on-source. The observational procedure included a dithering pattern that placed the target in the four quadrants of the detector. We acquired datacubes of 100 frames of 0.4 s integration time in each offset position. The plate scale,  $27.10 \pm 0.10 \text{ mas/pix}$ , and true north orientation of the detector,  $-0.48 \pm 0.25$  degrees, were derived using the astrometric calibrator  $\theta$  Ori<sup>1</sup> C observed in April 2010.

For the  $K_s$ -band data we used the S27 objective and the same strategy, but integrating in datacubes of 100 frames with 0.5 s of individual exposure time. We spent a total of 20 min on-source, and we used two stars, HD 102260 and HD 101251, as calibrators.

All data were reduced using a custom pipeline detailed in Lacour et al. (in prep.). In brief, each frame is flat-fielded, dark-subtracted, and bad-pixel-corrected. The complex amplitudes of each one of the  $7 \times 6/2 = 21$  fringe spatial frequencies were then used to calculate the bispectrum, from which the argument is taken to derive the closure phase. Lastly, the closure phases were fitted to a model of a binary source.



**Fig. 1.** Results from the  $L'$  SAM observations: a companion candidate is detected at  $61.8 \pm 7.4 \text{ mas}$  from the central source with a flux ratio of  $0.92 \pm 0.20\%$  in  $L'$ . *Upper left panel:*  $\chi^2$  as a function of the position of companion candidate (degrees of freedom = 314). The black circle corresponds to the imaging resolution of the telescope ( $1.22\lambda/D$ ). *Upper right panel:* best fit of the model of the companion (solid line) overplotted on the deconvolved phase. *Lower panel:* orientation of companion detections made using each of the nine individual data files plotted in raw detector coordinates. Spurious structures should appear fixed, while real features will rotate with the sky, as illustrated by the overplotted solid line that depicts the expected orientation for an object with a sky position angle of 78 degrees.

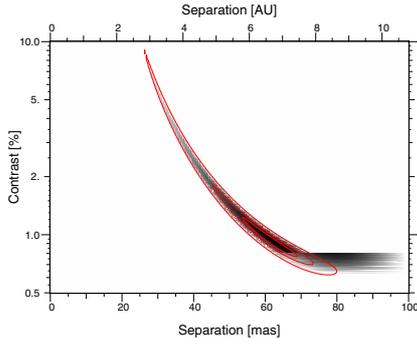
## 4. Main results

### 4.1. $L'$ detection

The three free parameters of the fit are the flux ratio, the separation, and the position angle of the companion candidate. The upper left panel of Fig. 1 depicts the minimum  $\chi^2$  as a function of position angle and separation. For an arbitrary fit,  $\chi^2$  is high (reduced  $\chi^2$  of  $\approx 9$ ), but the map shows a clear minimum for a companion to the west of the star. The phase corresponding to the best-fit model is shown in the right panel of the same figure. It consists of a sinusoidal curve with a specific angular direction, and a period of half the resolution of the 8.2 m telescope. In the same figure we plotted the deconvolved phases from the measured closure phases that were projected onto the orientation of the best-fit binary.

The best-fitting companion parameters for the  $L$ -band data are a separation of  $61.8 \pm 7.4 \text{ mas}$ , a position angle of  $78.5 \pm 1.2$  degrees, and a fractional flux with respect to the central object of  $0.92 \pm 0.20\%$ . To confirm the validity of the detection, each one of the nine star+calibrator data pairs was also analyzed separately. Because the observations were taken in “pupil tracking mode”, all optical and electronic aberrations should remain at frozen orientation on the detector, while a real structure on the sky will rotate with the azimuth pointing of the telescope (close to the sidereal rate). This expected rotation of the detection is illustrated in Fig. 1, which strongly argues against an instrumental artifact.

The detection error bars reported above are  $1-\sigma$ , but owing to the low separation, there is a strong degeneracy between



**Fig. 2.** Error contours as a function of separation and flux ratio in the  $L'$  filter. The contour levels correspond to  $1\text{-}\sigma$ ,  $2\text{-}\sigma$ , and  $3\text{-}\sigma$ . The upper horizontal labels provide the separation in astronomical units assuming a distance of 108 pc.

separation and flux ratio. This is highlighted in the contours shown in Fig. 2. The limits of the  $3\sigma$  contours correspond to a spread of parameters between flux ratio of 9% at 26 mas, and 0.6% at 80 mas.

#### 4.2. $K_s$ upper limit

We did not detect any source around T Cha in the  $K_s$ -band data. Figure 3 shows the  $1\text{-}\sigma$ ,  $2\text{-}\sigma$ , and  $3\text{-}\sigma$  sensitivity curves as a function of the separation to the central source. The data analysis shows that we can rule out a companion between 40 and 62 mas, with contrast ratios varying between 1.3% and 0.83%, respectively, at 99% confidence.

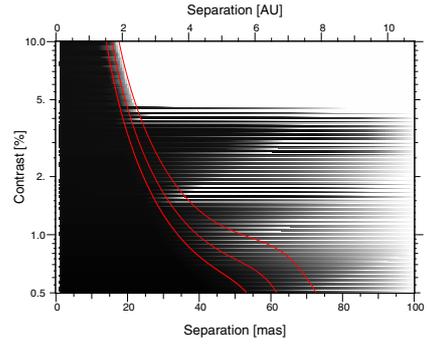
#### 4.3. Physical parameters

According to Sect. 4.1, we have detected a companion candidate at a separation and position angle of  $61.8 \pm 7.4$  mas and  $78.5 \pm 1.2$  degrees, respectively, and a flux ratio of  $0.0092 \pm 0.0020$ . Assuming a distance of  $108 \pm 9$  pc, the separation between the star and the companion candidate is  $\sim 6.7 \pm 1.0$  AU. This lies well within the disk gap of T Cha, according to the Brown et al. (2007, 0.2–15 AU) and Olofsson et al. (2011, 0.17–7.5 AU) disk models.

The flux ratio between the primary and the companion translates into a difference of magnitude of  $\Delta L' = 5.1 \pm 0.2$  mag. Because our observational methods are not optimized for photometry, we instead rely on  $L$ -band magnitudes for T Cha from the literature. The reported Johnson  $L$ -band ( $\lambda_c = 3.45 \mu\text{m}$ ,  $\Delta\lambda = 0.472 \mu\text{m}$ ) brightness of T Cha is  $5.86 \pm 0.02$  mag (Alcala et al. 1993), while the IRAC channel-1 ( $3.55 \mu\text{m}$ ,  $\Delta\lambda = 0.75 \mu\text{m}$ ) brightness is  $5.74 \pm 0.06$  mag. For the purpose of this paper, we assume an  $L'$  magnitude of  $5.8 \pm 0.1$  mag for the primary. Our measured contrast ratio then implies  $L' \sim 10.9 \pm 0.2$  mag for the companion candidate.

We can provide a  $3\text{-}\sigma$  limit of  $\Delta K_s > 5.2$  mag at the separation and position angle of the  $L'$  detection for the  $K_s$ -band data. Because T Cha itself shows  $K_s = 6.95 \pm 0.02$  mag (Cutri et al. 2003), the limit to the companion candidate brightness would be  $K_s > 12.15$  mag.

The extinction curve derived for T Cha using optical data seems significantly flatter than that from the interstellar medium (Schisano et al. 2009). However, because the disk extinction curve is not well known in the infrared regime, we corrected the observed magnitudes as a first approximation using the Mathis (1990) extinction curve with  $R_V = 5$ , and assuming



**Fig. 3.** Contrast in the  $K_s$ -band data. The solid red lines represent the  $1\text{-}\sigma$ ,  $2\text{-}\sigma$ , and  $3\text{-}\sigma$  upper limits at different separations from the central source. We estimate a  $3\text{-}\sigma$  upper limit of 0.83% at 62 mas, that is, at the position of the  $L'$  detected source.

$A_V = 1.7$  mag. We obtained  $A_{K_s} \sim 0.2$  mag and  $A_{L'} \sim 0.1$  mag, which results in magnitudes of  $L' = 10.8 \pm 0.2$  and  $K_s > 11.95$  mag.

## 5. Discussion

We have detected a source within the disk gap of T Cha. We will now discuss the possible nature of this object, keeping in mind that a detection at a single epoch and waveband provides limited information.

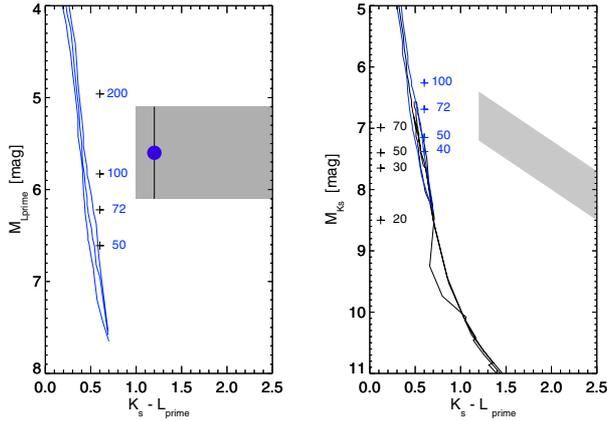
If we assume the two objects are co-moving and at a distance of  $108 \pm 9$  pc, the companion candidate would show absolute magnitudes of  $M_{L'} = 5.6 \pm 0.5$  mag, and  $M_{K_s} > 6.8$  mag. We used these values to place the object in two magnitude-color diagrams (Fig. 4). Assuming they are coeval, and assuming an age for the system of  $7 \pm 2$  Myr, both diagrams show that the observed properties are inconsistent with any unextincted photosphere at the age and distance of T Cha, according to the NextGen (Baraffe et al. 1998) and DUSTY (Chabrier et al. 2000) models<sup>1</sup>.

The companion candidate shows a very red  $K_s - L'$  color. A possible explanation for this  $K_s - L'$  excess would be a significant amount of dust around the object. If this scenario is correct, it would imply that the object is young, which would strengthen the case for a physical companion, and moreover according to Fig. 4b, the  $K_s$  upper limit would place it in the substellar (brown dwarf) regime.

Brown dwarf (BD) companions to stars are rare, as we know from radial velocity studies of samples of nearby stars (e.g. Grether & Lineweaver 2006), giving rise to the so-called ‘‘Brown Dwarf Desert’’. Although this could be interpreted as evidence against a BD for the T Cha companion, the separation of 6.7 AU places it near to the known shores of this desert (longer period companions are not well studied). Indeed, Kraus et al. (2011) claim that intermediate separation ranges (5–50 AU) show no evidence for this desert, which makes T Cha system interesting whether or not the companion mass lies above or below the BD cutoff.

Because disk gaps can be the result of dust clearing owing to planet formation, we also investigated if the companion candidate could be a recently formed planet within the disk. The T Cha system shows properties that are consistent with this scenario. First, the object is detected well within the disk gap. The total disk mass derived by Olofsson et al. (2011) is  $1.74 \pm 0.25 \times 10^{-2} M_\odot$ , while the average accretion rate is

<sup>1</sup> We have used the latest NextGEN and DUSTY models (Allard et al. 2010) convolved with the NACO filters.



**Fig. 4.** Magnitude-color diagrams with the T Cha companion candidate. *Left:* the solid lines show NextGEN models for 5, 7, and 10 Myr, while the shaded area represents the  $K_s - L'$  limit. We provide masses (in  $M_{\text{Jup}}$ ) for an age of 7 Myr. *Right:* the solid lines correspond to the NextGEN (blue) and DUSTY (black) models for 5, 7, and 10 Myr, and the masses are derived for an age of 7 Myr. The shaded area shows the possible location of the companion candidate, according to the derived  $M_{K_s}$  and  $K_s - L'$  limits.

$4 \times 10^{-9} M_{\odot}/\text{yr}$ . These properties seem consistent with a planet-forming disk according to Alexander & Armitage (2007), keeping in mind that both measurements can be affected by large uncertainties. If this is the case, the evolutionary models used here are not well suited to derive the mass of planetary objects, because we are probably observing the planet at the initial formation phase, when the brightness depends only on the accretion history and accretion rate. Indeed, one of the biggest advantages of observing transitional disks is that recently formed planets are probably still accreting material and therefore should be in their brightest evolutionary phase.

Additional observations are needed to shed light on the nature of this exciting object, the first potential substellar object detected within the gap of a transitional disk. In particular, observations that detect this object at other wavelengths or determine the disk position angle and inclination would be most useful.

## 6. Conclusions

We have observed T Cha with NACO/SAM in two filters,  $L'$  and  $K_s$ . Our main results can be summarized as follows:

- We detected a faint companion around T Cha at  $62 \pm 7.4$  mas of separation, position angle of  $78.0 \pm 1.2$  degrees, and contrast ratio of  $\Delta L' = 5.04 \pm 0.2$  mag. We did not detect any source in the  $K_s$ -band. The  $3\text{-}\sigma$  contrast ratio at a separation of 62 mas is 0.82%, that is  $\Delta K_s > 5.2$  mag.
- If T Cha and the detected object are bound, and assuming a distance of 108 pc, the faint companion lies at 6.7 AU, that is, within the disk gap of the central source.

- If T Cha and its companion are bound and coeval, the infrared magnitude-color diagrams show that the object photometry is inconsistent with any unextincted photosphere at the age and distance of T Cha when compared with the evolutionary tracks.
- The companion candidate displays a strong  $K_s - L'$  excess, which could be explained by a significant amount of dust around it. This scenario would strengthen the case of a physical companion and, according to the  $K_s$  upper limit, it would place the object in the substellar regime.
- The overall properties of the T Cha system also suggest that the newly detected source might be a recently formed planet within the disk. In this case, suitable planetary formation models are needed to derive its physical properties.

Second epoch observations in different photometric bands are mandatory to confirm if the object is bound, and to properly characterize it.

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