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Letter to the Editor

A companion candidate in the gap of the T Cha transitional disk*

N. Huélamo[1], S. Lacour[2], P. Tuthill[3], M. Ireland[3], A. Kraus[4], and G. Chauvin[5]

[1] Centro de Astrobiología (INTA-CSIC); ESAC Campus, P.O. Box 78, E-28691 Villanueva de la Cañada, Spain
e-mail: nhuelamo@cab.inta-csic.es
[2] Observatoire de Paris, LESIA/CNRS UMR, 5 place Jules Janssen, Meudon, France
[3] Sydney Institute for Astronomy, School of Physics, University of Sydney, NSW 2006, Australia
[4] Hubble Fellow; University of Hawaii-IfA, 2680 Woodlawn Dr, Honolulu, HI 96822, USA
[5] Laboratoire d'Astrophysique de Grenoble, CNRS, Université Joseph Fourier, UMR 5571, BP 53, F-38041 Grenoble, Cedex 9, France

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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 was to look for very low-mass companions within the disk gap of T Cha.
Methods. We have observed T Cha in L' and K_s with NAOS-CONICA, the adaptive optics system at the VLT, using sparse aperture masking.
Results. We have detected a source in the L' data at a separation of 62±7 mas, position angle of ∼78±1 degrees, and a contrast of $\Delta L' = 5.1 \pm 0.2$ mag. The object is not detected in the Ks band data, which shows a 3-σ contrast of $\Delta K_s > 5.2 \pm 0.2$ 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' photometry with evolutionary tracks indicates a companion mass of $\sim$0.11 $M_\odot$. However, the fact that we do not detect it in K_s, together with its large $K_s - L'$ color, allows us to reject such a stellar companion. The K_s upper limit places the object close to the substellar regime, but its extremely red $K_s - L'$ color (>1.25 mag) is inconsistent with any brown dwarf at the age and distance of T Cha. One possible explanation is that the companion is a very low-mass star or BD surrounded by a significant amount of dust responsible of the $K_s - L'$ excess. An 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. Instrumentation: adaptive optics, high angular resolution – Stars: brown dwarfs, planetary systems – Stars (individual): T Cha

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 the presence of gaps or holes within the disk. These gaps and holes can be created by several mechanisms, e.g. the presence of a close stellar companion, disk photoevaporation, grain growth or a planet formed within the disk. The presence of a planet forming within the disk is expected to generate a gap as dust and gas accretes onto the 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 1–10 μm and a very steep rise between 10–30 μm. 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 been recently detected by Olofsson et al. (submitted). Since one of the possibilities is that the gap has been cleared by a very low-mass object, we have 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 ϵ Cha association (Torres et al. 2008). It is a G8-type star **with a mass of** $\sim$ **1.5** $\mathbf{M_\odot}$, classified as a a Weak-lined T Tauri star based on the H_α equivalent width from single epoch spectroscopy (Alcala et al. 1993). Subsequent photometric and spectroscopic monitoring has indicated a strong variability of this line, showing significant changes in its equivalent width, intensity, and profile (Gregorio-Hetem et al.

Send offprint requests to: N. Huélamo

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1992; Alcala et al. 1993; Schisano et al. 2009). If the line is related to accretion episodes, then the average accretion rate is $\dot{M} = 4\times\ 10^{-9}\ M_{\odot}/yr$.

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 ϵ 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 ϵ Cha members. Finally, a dynamical evolution study of the η Cha cluster, which probably belongs to the ϵ 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 pc±15 pc. A more reliable value of 100 pc was obtained using proper motion studies (Frink et al. 1998; Terranegra et al. 1999). Torres et al. (2008) provided a kinematical distance of 109 pc for T Cha, and an average value of 108±9 pc for the whole association. We have adopted the latter value for this paper.

Finally, we note that previous works based on radial velocity (RV) and direct imaging and coronographic 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. (submitted)). SAM observations allow to fill the gap between 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. *L'* observations were obtained on March 2010 under excellent atmospheric conditions (average coherent time of τ_0=8 ms, and average seeing of 0.″6), while K_s band data were obtained on July 2010 under moderate atmospheric conditions (τ_0=4 ms, and seeing of 1.″0).

On March 2010, T Cha was observed with the L27 objective, the 7-hole mask and the L' filter (λ_c= 3.80μm, $\Delta\lambda$= 0.62 μm). The target and a calibrator star (HD 102260) were observed during 10 minutes each. We repeated the sequence star+calibrator 9 times, integrating a total of 48 minutes 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 sec integration time in each offset position. **The plate scale, 27.10±0.10 mas/pix, and True North orientation of the detector, -0.48±0.25 degrees, were derived using the astrometric calibrator θ Ori[1] C observed on April 2010.**

In the case of the K_s-band data, we used the S27 objective and the same strategy but integrating in datacubes of 100 frames with 0.5 sec of individual exposure time. We spent a total of 20 minutes 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 preparation). 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 are then used to calculate the bispectrum, from which the argument is taken to derive the closure phase. Lastly, the closure phases are fit to a model of a binary source.

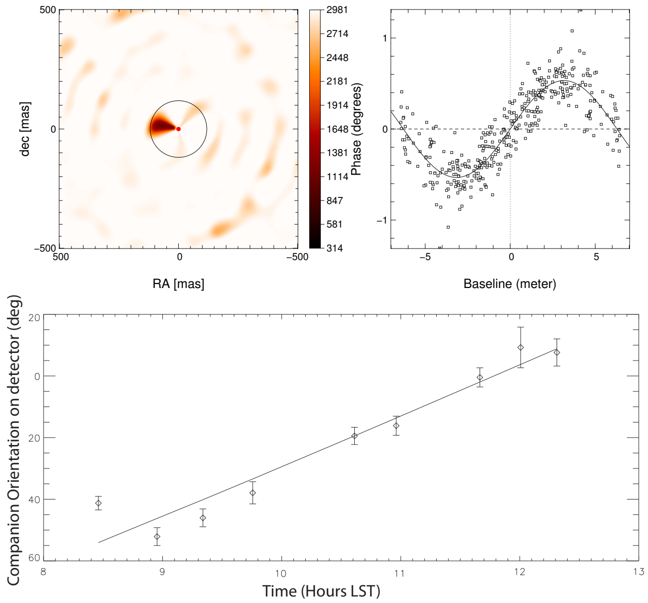

Fig. 1. Results from the L' SAM observations: a companion candidate is detected at 61.8 ± 7.4 mas from the central source with a flux ratio of 0.92±0.20 % in *L'*. *Upper Left panel:* χ^2 as a function of the position of companion candidate (degrees of freedom = 314). The black circle correspond to the 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 9 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 depicting the expected orientation for an object with 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 χ^2 as a function of position angle and separation. For an arbitrary fit, χ^2 is high (reduced χ^2 of ≈ 9), however the map shows a clear minima for a companion to the west of the star. The phase corresponding to the best fit model is shown on 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 meter telescope. On the same figure are plotted phases deconvolved from the measured closure phases and projected onto the orientation of the best-fit binary.

The best-fitting companion parameters for the L-band data are separation of 61.8 ± 7.4 mas, position angle 78.5 ± 1.2 degrees and a fractional flux relative 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. As observations were taken in 'pupil tracking mode', all optical and electronic aberrations should remain at frozen orientation on the detector, while 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**

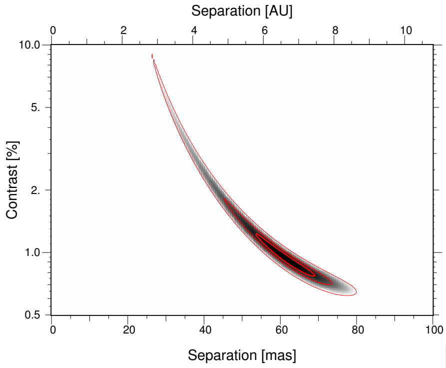

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Fig. 2. Error contours as a function of separation and flux ratio in the L' filter. The contour levels correspond to 1-σ, 2-σ and 3-σ. The upper horizontal labels provide the separation in astronomical units assuming a distance of 108 pc.

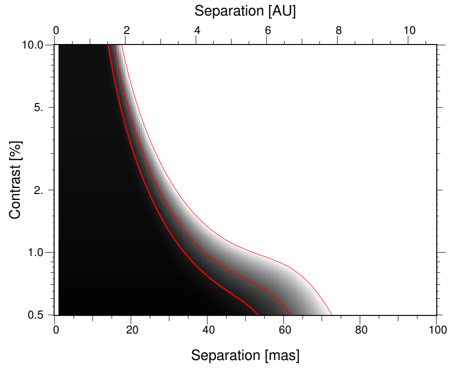

Fig. 3. Contrast in the K_s-band data. The solid red lines represent 1-σ, 2-σ and 3-σ upper limits at different separations from the central source. We estimate a 3-σ upper limit of 0.83% at 62 mas, that is, at the position of the L' detected source.

Fig. 1 which strongly argues against an instrumental artifact.

The detection error bars reported above are 1-σ, but due to the low separation, there is a strong degeneracy between separation and flux ratio. This is highlighted in the contours shown in Fig. 2. The limits of the 3 σ contours correspond to a spread of parameters between flux ratio of 9% at 26 mas, and 0.6% at 80 mas. **The probability of chance alignment with a background star anywhere within the 0.5 arcsec field of view of the masking interferometry, at a contrast of less than 6 magnitudes is about 1 part in 20,000**.

4.2. K_s upper limit

In the case of the K_s-band data, we have not detected any source around T Cha. Figure 3 shows the 1-σ, 2-σ, and 3-σ sensitivity curves as a function of the separation to the central source. The data analysis shows that we can rule out the presence of 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 section 4.1, we have detected a companion candidate at a separation and position angle of 61.8±7.4 mas and 78.5±1.2 degrees, respectively, and a flux ratio of 0.0092±0.0020. Assuming a distance of 108±9 pc, the separation between the star and the companion candidate is ~6.7±1.0 AU. This lies well within the disk gap of T Cha, **according to Brown et al. (2007, 0.2-15 AU) and Olofsson et al. (submitted, 0.17-7.5 AU) disk models**.

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

In the case of the K_s band data, we can provide a 3-σ upper limit of ΔK_s>5.2 mag at the separation and position angle of the L' detection. Since T Cha itself shows K_s=6.95±0.02 mag (Cutri et al. 2003), the upper limit to the companion candidate brightness would be K_s >12.15 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±9 pc, then the companion candidate would show absolute magnitude $M_{L'}$= 5.7±0.5 mag. Assuming they are coeval, and an age for the system of 7±2 Myr, Baraffe et al. (1998) NextGen evolutionary models[1] predict a mass of ~0.11 M$_\odot$ and $T_{eff} \sim 3100\,K$ for the companion candidate (see Fig.4a). However, such a stellar companion would have been easily detected in our K_s-band observations, since it would show ΔK_s=4.35 mag. **In addition, the expected $K_s - L'$ color would be ~0.4 mag, while we observe a color redder than 1.25 mag. Hence, if bound, such a stellar companion can be ruled out (see Fig. 4a).**

The K_s upper limit places the companion in the substellar regime (see Fig. 4b), according to NextGen models ($M < 50 \pm 20\,M_{Jup}$), and in the very low-mass stellar or substellar regime ($M <$ 70±20 M_{Jup}) according to DUSTY models (Chabrier et al. 2000)[1]. However, the lower limit on the $K_s - L'$ color is not consistent with that predicted for any object at the age and distance of T Cha. One possibility is that the object is a very low-mass star or substellar companion surrounded by a significant amount of dust responsible of the $K_s - L'$ excess. Current observations do not allow to confirm this hypothesis.

If substellar, it is worth to mention that BDs companions to stars are known to be rare from ra-

[1] We have used the latest NextGEN and DUSTY models (Allard et al. 2010) convolved with the NACO filters

dial 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. (submitted) claim that intermediate separation ranges (5–50 AU) show no evidence for such desert, and so the T Cha system is interesting whether or not the companion mass lies above or below the BD cutoff.

Since disk gaps can be the result of dust clearing due to planet formation, we have 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. (submitted) is 1.74±0.25×10^{-2} M$_\odot$**, while the average accretion rate is $4{\times}10^{-9}\,M_\odot/yr$. 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. In fact, one of the biggest advantages of observing transitional disks is that recently formed planets are probably still accreting material and therefore they 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 have detected a faint companion around T Cha at 62 ± 7.4 mas of separation, position angle of 78.0±1.2 degrees, and contrast ratio of $\Delta L' = 5.04 \pm 0.2$ mag. We have not detected any source in the K_s-band. The 3-σ contrast ratio at a separation of 62 mas is 0.82%, that is ΔK_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, and assuming and age of 7 Myr, the L' detection corresponds to a mass of ~0.11 M$_\odot$ for the companion. However, the non-detection in K_s, **together with the extremely red $K_s - L'$ color, allows us to reject such a stellar companion.**
- **The K_s upper limit alone places the companion close to the substellar regime but with a lower limit to the $K_s - L'$ color inconsistent with any very low-mass star or BD at the age and distance of the source. One possibility is that the object is surrounded by a significant amount of dust responsible of the observed $K_s - L'$ excess.**
- The overall properties of the T Cha system 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**.

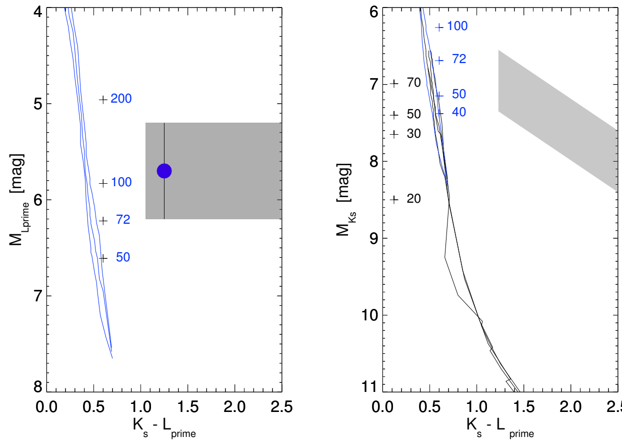

Fig. 4. Magnitude-color diagrams with the T Cha companion candidate. **Left:** The solid lines show NextGEN models for 5,7, and 10 Myr, while the shaded area represents the $K_s - L'$ limit. We provide masses (in M$_{Jup}$) for an age of 7 Myr; **Right:** The solid lines correspond to NextGEN (blue) 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.

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

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